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Air Bubbler Ice Control Experiment In Thunder Bay, Ontario

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AIR BUBBLER ICE CONTROL EXPERIMENT IN THUNDER BAY, ONTARIO

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THUNDER BAY, ONTARIO

JULY, 1983

PROJECT NO. 82-144-01

V. B. COOK CO. LIMITED

CONSULTING ENGINEERS

THUNDER BAY, ONTARIO

DISCLAIMER

The contents of this report reflect the views of the author and not necessarily the official views or policies of Transport Canada.

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17. Abstract

This report describes part of a continuing programme studying ice management techniques in the port of Thunder Bay, Ontario. Specifically, this report concerns the monitoring of ice conditions and bubbler performance in the harbour slip serving United Grain Growers Elevator 'M' and Manitoba Pool Elevator #1 in Thunder Bay, Ontario, during the winter season of 1982/83.

A novel air bubblers, using moveable rakes, were installed in the mid-slip position and its performance was evaluated along with that of a conventional fixed bubbler installation at the edge of the slips. The moveable air bubblers were conceived as a means of avoiding damage to the ice management system by prop wash, dragged anchors, etc. Unfortunately, owing to mechanical problems experienced with the air supply, serious problems were experienced with the rakes freezing up; as a result, they had very limited success in suppressing ice in the mid-slip area.

Two computer models simulating the design and operation of bubbler systems were successfully developed apart of this project. These models allow the combination of air bubbler system design data and environmental data to predict when the air bubbler system should be started in the Spring to achieve a desired level of ice suppression by a specified date.

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17. Résumé

Ce rapport décrit un aspect du programme d'étude en cours sur les techniques de maîtrise des glaces dans le port de Thunder Bay, en Ontario. Il concerne plus particulièrement la surveillance des conditions d'englacement et le résultat obtenu avec le système à bulles d'air dans les bassins réservés à l'élévateur "M" de la United Grain Growers et à l'élévateur n° 1 de la Manitoba Pool à Thunder Bay, tout au long de l'hiver 1982/1983.

Des variantes du système à bulles d'air, comportant des rampes de diffusion mobiles, ont été placées à mi-chemin dans le bassin et leurs performances comparées à celles d'un système classique à bulles d'air placé au bord du bassin. Les systèmes à rampes mobiles sont à l'abri des dangers causés par les remous dus aux hélices, les ancres que l'on traîne, etc. Malheureusement, le système à rampes mobiles a connu de graves ennuis d'alimentation qui ont entraîné le gel des rampes, de sorte que les opérations de déglaçage au milieu du bassin n'ont eu qu'un succès très relatif.

Deux modèles mathématiques simulant les caractéristiques et le fonctionnement des systèmes à bulles d'air ont été élaborés. Combinant les données sur le système à bulles d'air et celles concernant l'environnement, ces modèles pourront déterminer le meilleur moment de mise en marche du système à bulles d'air au printemps, de manière à atteindre le niveau de déglaçage voulu à une date donnée.

18. Mots-clés	19. Diffusion
Maîtrise des glaces, Gestion des glaces, Déglaçage, Ports, Quais, Système à bulles d'air	Le CDT dispose d'un nombre limité d'exemplaires

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The assistance of all other parties who helped with this evaluation is greatly appreciated.

SUMMARY

This report is part of a continuing programme studying ice management techniques in Thunder Bay, Ontario.

Specifically, this report concerns the monitoring of ice conditions and bubbler performance in the harbour slip serving United Grain Growers Elevator 'M' and Manitoba Pool Elevator #1 in Thunder Bay, Ontario, during the winter season of 1982/83.

As a result of this study our understanding and ability to predict the performance of a line bubbler mounted along the sheet piling of a slip has been reinforced.

Efforts to find a suitable and low maintenance replacement for the mid-slip line bubbler (an effective but expensive bubbler) have not been successful.

Two computer models simulating bubbler systems have been successfully developed. The first model will be used to optimize the physical and operating parameters of any line bubbler whose approximate configuration can be defined. The second model predicts, using the simultaneous effects of freezing & melting, the performance of a bubbler system.

It is concluded that line bubbler systems are a viable means of melting ice along the edge of grain elevator slips, however it is recommended that other technologies be tried to improve the removal of ice in the centre of the slip.

It is also concluded that the ice melting performance of an air bubbler can be simulated using a micro computer and this system performance model can be used to determine when a bubbler system should be started up in the Spring to attain an expected opening date for the shipping season.

TABLE OF CONTENTS

1.	INTRODUCTION		1
2.	DISCUSSION		
	2.1	System	2
	2.2	Procedure and Observations	3
	2.2.1	General	3
	2.2.2	Rakes	4
	2.2.3	Air Flow	4
	2.2.4	Climatic Conditions	5
	2.2.5	Water Temperature	5
	2.2.6	Ice Thickness	5
	2.2.7	Power Consumption	6
	2.3	Theoretical Considerations	7
	2.3.1	Diffuser - Preliminary	7
	2.3.2	Diffuser - Using The Programme	10
	2.3.3	Bubbler Performance - Preliminary	12
	2.3.4	Bubbler Performance - Using the Programme	19
3.	CONCLUSIONS		20
4.	REFERENCES		21
5.	DRAWINGS, PHOTOGRAPHS AND COMPUTER PRINTOUTS		22

ILLUSTRATIONS

Fig. 1 - Width of Induced Flow Page 13

Fig. 2 - Variation of Heat Transfer Coeff. Page 14

Fig. 3 - Heat Transfer Coeff. Page 15

LIST OF DRAWINGS

500 Bubbler System Flow Diagram

501 Proposed Operation of Perpendicular Rakes

502 Proposed Operation of Parallel Rakes

503 Plan for Ice Metering Stations

504 Ice Thickness

507 Mid-Slip Diffusers (Rakes)

508 Air Metering Station

LIST OF PHOTOGRAPHS

Mid-Slip Diffuser (Rake) Propagation Test

Parallel Rakes in Operation

Slip Aerial Photographs - March 2,6,11,14,17,26,29 and 31.

1. INTRODUCTION

The bubbler system studied in this report was installed in the fall of 1982 in the harbour slip between Manitoba Pool Elevator #1 and United Grain Growers Elevator "M" in Thunder Bay, Ontario.

The system consists of approximately 530 m of line bubbler diffuser pipe installed along the sheet piling at the bottom of the slip on the Manitoba Pool wharf and similarly 570 m on the United Grain Growers Elevator "M" wharf.

Unlike the system studied in the Saskatchewan Pool 7A slip (ref. TP-3797E, Kamo, Nelson, 1982) there is no "mid slip" line bubbler diffuser pipe. This configuration of bubbler, although effective at melting ice, proved to be too prone to anchor and propwash damage. Subsequent repairs were expensive and it was therefore decided to adopt a different design of diffuser unit (rake) similar to units used with success at Thunder Bay Terminals, a coal handling facility approximately 5 km south of this location.

To supply air for six of these units, a plastic manifold line was erected on the UGG "M" wharf.

The study of this system was co-sponsored by the Lakehead Harbour Commission and Transport Canada's Marine Administration and Transportation Development Centre as part of a continuing programme investigating various techniques of ice control in the harbour at Thunder Bay.

This report describes the monitoring carried out and presents the data collected. The results are analyzed and compared with computer models developed to simulate these bubbler systems.

V. B. Cook Co. Limited, Consulting Engineers, were engaged to provide appropriate monitoring and to report on the performance of the installed air bubbler system.

From past bubbler experiment experience and after researching related ice technology publications, it was decided to measure and monitor the following parameters:

- air pressure and flow
- compressor power consumption
- slip water temperatures
- climatic conditions
- ice thickness growth and deterioration
- general observations during the operational period

2. DISCUSSION

2.1 System

The flowsheet for the bubbler system installed in the UGG "M"/Manitoba Pool slip is shown on Drawing 500.

On each side of the slip, a 40 HP Grimmer Schmidt compressor with a rated capacity of 300 m^3/h free air at a nominal pressure of 690 kPa gauge provides its respective line bubbler with compressed air.

Each compressor discharges via a 50 mm pipe into a 0.28 m^3 receiver. The 50 mm outlet from the receiver feeds two air metering stations each connected to a branch of the line bubbler system.

Details of the air metering stations are shown on Drawing 508. Air from the receiver feeds a 50 mm header and is split into two parallel branches. The air temperature is measured in the header. A condensate trap and drain valve are located at the bottom of the header for periodic cleaning.

Each branch of the air metering station is fabricated from a 50 mm diameter pipe and includes a 50 mm isolation valve, an annubar flow sensor device and a flow regulating valve. A portable differential pressure meter connects to each annubar device. Each branch is connected to the distribution pipe consisting of two parts: the delivery section and the diffuser section. The delivery section consists of approximately 6 m of 38 mm diameter rubber hose and is connected to a vertical pipe attached to the side of the wharf. The vertical pipes are internally heat traced and carry the air approximately 10 m from the top of the wharf to the bottom of the slip.

The diffuser sections are connected to the bottom of the vertical pipes and rest on the slip bottom. Each diffuser is made up of two parts. The first part is made from a 38 mm diameter galvanized pipe with 1.6 mm diameter holes drilled in the pipe wall at approximately 6.7 m centres. The second part is made from a 25 mm diameter galvanized pipe and has 2.4 mm diameter holes drilled in the pipe wall on 6.7 m centres. The inshore and outshore diffusers on the Manitoba Pool side are 195 m & 340 m long respectively. The inshore and outshore diffusers on the UGG "M" side are 280 m & 295 m long respectively.

A third compressor, a 75 HP Atlas Copco unit with a rated capacity of 370 m^3/h free air at a nominal pressure of 690 kPa gauge provides compressed air to the third part of the system, a 50 mm plastic manifold line attached to the UGG "M" wharf.

The plastic manifold line acts as a compressed air supply for the mid slip diffusers (rakes).

Details of the mid slip diffusers (rakes) are shown on Drawing No. 507. Air from the plastic manifold is supplied to each rake through one of 20 tee outlet stations on the plastic manifold. A 19 mm compressed air hose connects the tee outlet station to the rake.

Six rakes were fabricated, three for use inshore and three for use outshore. The mode of operation of the inshore rakes is shown on Drawing #501. Each rake was pulled across the slip at a rate dictated by its capacity to melt ice and clear a path for itself through the ice. Because the path of movement of these units is essentially perpendicular to the slip, these units are termed perpendicular rakes.

The mode of operation of the outshore rakes is shown on Drawing #502. Because these units move parallel to the slip, they are termed parallel rakes.

2.2 PROCEDURE/OBSERVATIONS

2.2.1 General

The installation of the bubbler diffuser sections and plastic manifold was accomplished from mid-September to the first week of October, 1982.

One of the tee stations on the plastic manifold was damaged September 30, 1982 by a dragging grain boat cable, and required subsequent repair.

A prototype rake (see Photographs) and the bubbler diffusers were tested November 22, 1982.

The bubble propagations for each orifice were observed and the precise location of each bubbler was marked along both wharves.

During December 1982, UGG "M" and Manitoba Pool #1 personnel provided electrical and piping services necessary to complete the installation of the compressors and plastic manifold.

The ice metering stations and a control set of ice thicknesses were established February 28, 1983. Regular metering (every 2 days) of these stations was accomplished using the proven chain saw/measuring wire method (ref. TP-3797E, Kamo, Nelson, 1982) and continued until March 24, 1982.

2.2.2 Rakes

The concept of using rakes to replace the mid-slip bubbler (used in the 1981/82 project) evolved because it became apparent that the mid-slip bubbler, though effective, was a very expensive apparatus to maintain due to its susceptibility to damage from prop wash, dragged anchors, etc.

The inshore and outshore rakes were installed using a gas driven ice auger.

The plastic manifold pipe was an initial maintenance problem due partly to its susceptibility to physical damage and partly to the substantial changes in length the line exhibited during very warm and very cold days.

Because of inadequate means of draining condensation, the inshore plastic manifold and rakes froze and were removed from service on March 11, 1982.

2.2.3 Air Flow

The operation of the air metering stations was greatly improved by replacing the pressure regulating valves (from the previous bubbler experiment) with globe valves and pressure gauges. The globe valves provided direct analog control of flow and the pressure gauges provided direct visual feedback.

It became evident early in the procedure that, in order to facilitate expedient data collection and to protect the station components from freezing, the stations had to be protected from the elements. The air metering stations were accordingly housed, or relocated indoors.

The configuration of the air metering station for the plastic manifold pipe proved to be entirely inadequate. Individual metering of airflow to each bubbler unit (diffuser or rake) is the only reliable means of establishing a flow to that unit, especially in the adverse climatic conditions these units operate in.

2.2.4 Climatic Conditions

The characteristics of this season's winter conditions were established from meteorological data published by Environment Canada from the Thunder Bay Airport. From the hourly temperature readings, the freezing degree days (below 0°C) and thawing degree days (above 0°C) were calculated from October 1, 1982 through to March 31, 1983. This detailed method of calculating freezing and thawing degree days was employed because it is more accurate than using the mean of the maximum and minimum daily temperatures as used by Environment Canada to calculate degree days.

2.2.5 Water Temperature

The measuring and reporting on the water temperature in the slip was conducted by Arctec Canada Ltd.

The conclusions which are pertinent to this study are quoted directly from their draft report of April 1983, as follows:

In slips where the bubbler system was in operation:

- Water temperature was between 0.1 and 0.3°C.
- Water temperature was almost constant throughout the depth.
- Water temperature was constant over the four-day period during which measurements were made.
- Water temperature was lower in the centre of the slip relative to the temperature measured at the slip port entrance.

2.2.6 Ice Thickness

A 39 station grid was established to measure ice thicknesses. Their positions are as shown on Drawing #503. The results of the monitoring from February 28 to March 24, 1983 are shown on Drawing #504.

The station locations were determined on the following basis:

.1 Stations 1, 2, 3, 13 & 14 - selected locations assumed to be close to the impingement zones of 5 bubblers and away from the influence of the wharf

sheet piling.

.2 Stations 4 to 12 plus 15 to 22 - a cross shaped intensive grid with the centre located over the third bubbler away from the corner of the Manitoba Pool wharf.

.3 Stations 23 to 30 - a "U" shaped pattern with bubbler impingement zones in the corners.

.4 Stations 31 to 39 - a line of stations traversing the slip from the Manitoba Pool side to the UGG "M" side.

The precautions taken to ensure the safety of the ice monitoring crew were better and more functional than in the previous (TP-3797E, Kamo, Nelson, 1982) study. The cumbersome and restrictive wet suits were replaced by hypothermia parkas. The annoying roping-off operations were replaced by two 16 m ropes tied to a light aluminum boat which was dragged around with the monitoring crew.

In addition to the ice metering results, aerial photographs showing qualitatively the ice deterioration were taken at regular intervals from February to March, 1983.

2.2.7 Power Consumption

Because of operational problems with other elements of the bubbler systems during the initial 10 days, the wattmeter readings were neglected. Additionally, the Manitoba Pool compressor operated erratically before finally breaking down during this same initial period. The Manitoba Pool readings, therefore, are for the period March 11 to March 31, 1981. The UGG "M" readings are for the entire month.

1. Manitoba Pool Bubbler Compressor:

$$\frac{14713.0 - 04827.8}{31 - 11} = 494 \text{ kWh/day}$$

2. UGG "M" Bubbler Compressor:

$$\frac{16556.9 - 00000.0}{31 - 1} = 552 \text{ kWh/day}$$

3. UGG "M" Rake Compressor:

$$\frac{25139 - 01768}{31 - 1} = 779 \text{ kWh/day}$$

2.3 Theoretical Considerations

The scope of the work of this study included the developing of two computer models which could be used by other designers to construct future bubbler systems.

2.3.1 Diffuser - Preliminary

The first model (diffuser) was developed to relate the controllable parameters, i.e., air flow and pressure, to the physical constraints of the waterfront location, i.e., depth and length of slip.

The model is based on the thermodynamic concept of reversible, adiabatic flow of an ideal gas through a nozzle.

The simulation starts at the beginning of the diffuser section so the initial conditions at this point must be determined as follows:

The average values of temperature and air flow at the entrance to the metering station were 49°C and .0644 m^3/sec (i.e. Q = .0322 m^3/sec per branch).

The temperature drop is now calculated across the metering station, through the flexible hose and down the vertical pipe to the beginning of the diffuser section. (The air pressure was metered at the entrance to the flexible hose (118 kPa avg.) and the pressure drop from that point to the beginning of the diffuser section is assumed to be negligible.)

.1 Temperature Drop Across Metering Station

The temperature drop across the metering station is calculated as follows:

T_i = 49°C	- temp. inside pipe
T_o = 30°C	- ambient temp.
L = 5 m	- eq. length of st'n.
D_i = .05252 m	- pipe ID
D_o = .06032 m	- pipe OD
R_o = 1.20127 kg/m^3	- density of air
h_i = .05588 kWh/hr m^2 °C	- inside film coef.

h_o = .00601 kWh/hr m^2 °C - outside film coef.

k = .04496 kWh-m/hr m^2 °C
- thermal cond. steel

$m' = R_o \times Q \times 3600$

$= 1.20127\ kg/m^3 \times .0322\ m^3/sec \times 3600\ sec/hr$

= 139.25 kg/hr - mass air flow

C_p = .00028 kWh/kg °C

- therefore the heat loss across the metering station is:

$$H_L = \frac{T_i - T_o}{\frac{1}{\P D_i L h_i} + \frac{\ln(D_o/D_i)}{2\P k L} + \frac{1}{\P D_o L h_o}}$$

$$= \frac{49 - (-30)}{\frac{1}{\P(.05)5x.05} + \frac{\ln(.06/.05)}{2\P x.04x5} + \frac{1}{\P(.06)5x.006}}$$

= .40021 kWh

- therefore the temperature drop across the metering station is:

dT = .40021/(.00028) x 139.25) = 10.26°C

- and the temperature exiting this section is:

T_A = 49 - 10.26 = 38.74°C

.2 Temperature Drop Through Flexible Hose

Similarly the temperature drop through the flexible hose is:

d_T = 23.56°C

- and the temperature exiting this section is:

T_B = 38.74 - 23.56 = 15.18°C

.3 Temperature Drop Down the Vertical Pipe

In calculating the temperature drop down the vertical pipe, the following two assumptions are made:

(i) the temperature drop in the short vertical section above the water is negligible.

(ii) because the pipe temperature is essentially the same as the water temperature (T_o = 1°C) the outside film co-efficient is very large and the third term in the denominator of the heat loss equation approaches zero i. e.

$$H_L = \frac{T_i - T_o}{\frac{1}{\pi D L h_i} + \frac{\ln(D_o/D_i)}{2\pi K L}}$$

- the temperature drop down the vertical pipe is:

d_T = 53.35°C

- since this value is greater than T_B (15.18°C) the temperature drop will be limited to the water temperature surrounding the pipe and will remain so for the entire length of the diffuser.

.4 Summary

The required initial conditions of pressure, temperature and flow at the beginning of the diffuser section are summarized as follows:

Pressure	118 kPa	(17.11 psig)
Temperature	1°C	(34°F)
Flow	.0322 m^3/sec	(68.25 scfm)

These values are used in the second and third runs (Section .4 Running the Programme) of the simulation. A pressure of 83 kPa (12 psig) is used in the first run to demonstrate the effect of insufficient initial pressure.

2.3.2 Diffuser - Using the Programme

.1 Parameters Governed by the Slip:

The slip depth and length control the number of bubbler orifices and their centre to centre spacing along the diffuser. For example, using the UGG "M" outshore diffuser, the following points are noted:

.1 Slip depth - 8.23 m (27 feet).

.2 Outshore diffuser length - 293 m (961 feet).

Ashton recommends that the maximum spacing not exceed 50% of slip depth or 3.96 m (13 ft.) maximum. This recommendation is based on observations of ratios which produced a good line bubbler characteristic.

The number of bubbler orifices is, therefore, 293/3.96 = 74 orifices.

.2 Diffuser Capacity:

Again referring to Ashton, we note that the lower and upper ranges of airflow for impingement zone and heat transfer coefficient sizing are .0001 $m^3/s/m$ to .005 $m^3/s/m$ (6.5 cfm/100 ft. to 32 cfm/100 ft). of diffuser. Assuming a 'rule of thumb' flow of .00047 m^3/sec (1 cfm) per bubbler orifice results in:

.00047 x 74/293 = .00012 $m^3/s/m$ (7.7 cfm/100 ft.)

$.0001 < .00012 < .005$ $m^3/s/m$ - checks

Note: The value that will actually be used in the computer model is the metered flow of .032 m^3/s (68.25 cfm).

The decision on what pipe size to use for each section of the diffuser is made by arbitrarily allowing a limit of 13.79 kPa (2 psi) pressure loss per 30.48 m (100 ft.).

- At .032 m^3/s (68.25 cfm) a 38 mm (1½ in.) diameter pipe is required
- At .016 m^3/s (34.13 cfm) a 25.4 mm (1.0 in.) diameter pipe is required.

.3 Orifice Diameters

The selection of orifice sizes can be made from a calculation assuming a diffuser pipe pressure, or the arbitrary selection of orifice sizes can be left to the computer model to evaluate.

.4 Running the Programme

The computer requests inputs for:

- Slip depth - 8.23 m (27 feet).
- Total diffuser length - 293 m (961 feet).
- 1st section diameter - 38.1 mm (1½").
- 1st section orifice diameter - 1.6 mm (.0625").
- 2nd section diameter 25.4 mm (1.0").
- 2nd section orifice diameter 1.98 mm (.0781").

For the first run, the following flow parameters are tried:

- Pressure - 82.74 kPa (12 psig).
- Temperature - 1.11°C (34°F).
- Air flow - .032 m^3/s (68.25 scfm).

This results in a loss of pressure at the 15th bubbler.

For the second run, the pressure and 2nd section orifice diameter are increased as follows:

- Orifice diameter - 2.38 mm (.0938").
- Pressure 118 kPa (17.11 psig).

This run results in a loss of capacity at the 63rd bubbler.

For the third run, the second section orifices are attenuated.

2nd Section Orifice diameter - 1.98 mm (.0781").

This run results in a fully operational system with a bit of extra pressure and almost no extra capacity.

A completely optimized set of parameters would exhibit no excess air at a pressure equal to the hydrostatic head outside the diffuser (= depth of slip).

.5 Summary

The optimum initial flow parameters for the bubbler system (as shown on Dwg. 500) operating at .00012 m^3/sec/m (7.7scfm/100FT) are 118 kPa (17.11 psig) and .0322 m^3/sec (68.25 scfm).

2.3.3 Bubbler Performance - Preliminary

The second model, (bubbler performance) was developed to predict the growth/decay of ice and to compare this growth/decay to the actual measured values.

The model used to simulate bubbler performance is based on Ashton, as outlined in "Air Bubbler Systems to Suppress Ice."

Before using the simulation, several parameters must be evaluated including the following:

.1 Width of the Induced Flow

The width of the induced flow is developed from Figure 1/ Ashton at an abscissa value of the slip depth, 8.23 m (27 ft.) and a unit flow rate of .0001 m^2/sec. The resulting ordinate value is:

$$2b = .8 \text{ m}$$

$$b = .4 \text{ m}$$

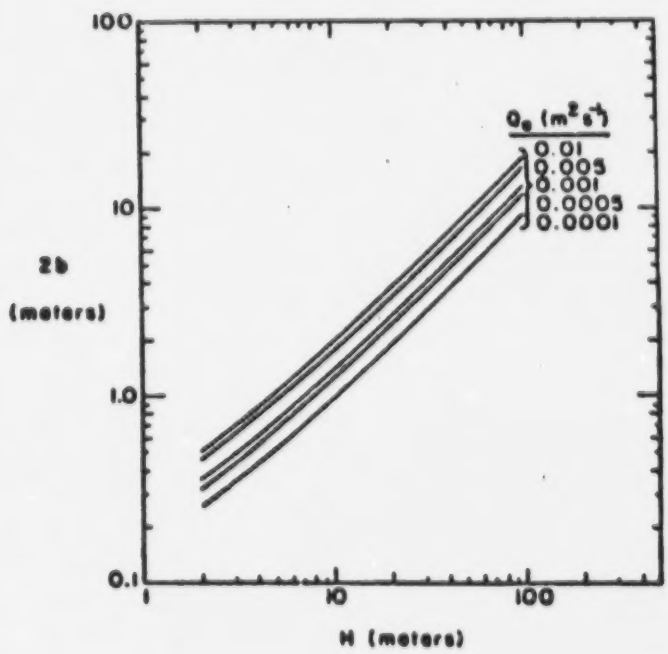


Figure 1. Width of induced flow as a function of diffuser submergence and air discharge rate (ref. Ashton, 1974).

.2 Selection of Demonstration Stations

From Drawing 504, Stations 17, 11 and 21 are arbitrarily selected to run on the simulation. Using the distances of these stations to the nearest bubbler and Figure 2/Ashton, the following table is constructed:

Station Number	Dist. y to Nearest Bubbler	y/b	Reduction Multiplier
17	1.30 m	3.25	.63
11	3.05 m	7.63	.47
21	5.72 m	14.30	.36

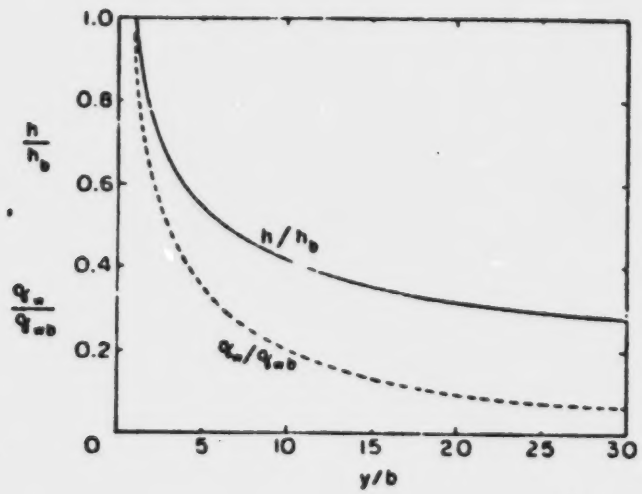


Figure 2. Variation of heat transfer co-efficient and heat transfer rate with distance outward from impingement region (ref. Ashton, 1974).

.3 Heat Transfer Coefficient

The heat transfer coefficient is developed from Figure 3/Ashton at an abscissa value of the slip depth, 8.23m and a unit flow rate of .0001 m^2/sec. The resulting ordinate value is:

$$H_b = 730 \text{ Joules/m}^2\text{s } ^\circ\text{C}$$

Applying the reduction multiplier from .2 above, the heat transfer coefficients at Stations 17, 11 and 21 become:

$$.63 \times 730 = 460 \text{ Joules/m}^2\text{s } ^\circ\text{C}$$

$$.47 \times 730 = 343 \text{ Joules/m}^2\text{s } ^\circ\text{C}$$

$$.36 \times 730 = 263 \text{ Joules/m}^2\text{s } ^\circ\text{C}$$

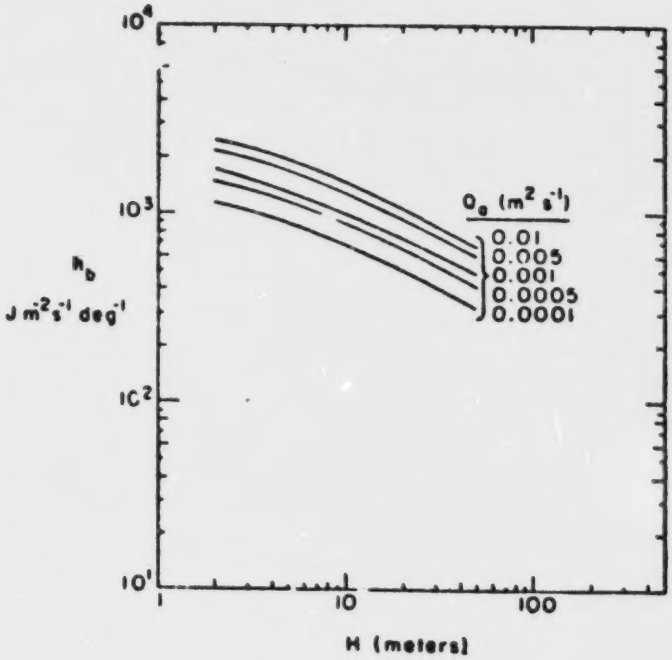


Figure 3. Heat transfer co-efficient averaged over the impingement region as function of diffuser submergence depth and air discharge rate (ref. Ashton, 1974)

.4 Water Temperature

Combining the results of the Arctec report on slip temperatures with the temperature readings from the 1981/1982 study, the water temperature at the beginning of the metering period was estimated to be .35°C.

.5 Air Temperature

Using recorded hourly temperatures for Thunder Bay during the metering period, the following table is constructed.

SUMMARY: TEMPERATURES AND PERIODS

Date	Total Degree Hours	Avg. Daily Temp. (°C)	Period Number	Period Duration (Days)	Avg. Period Temp. (°C)
Feb. 28	-192.4	-8.02		Bubbler Off	
Mar. 1	-272.4	-11.35		Bubbler Off	
Mar. 2	-130.3	-5.43	1	1	-7.36
Mar. 3	-62.3	-2.60	2	1	-1.80
Mar. 4	-23.7	.99	3	1	+.36
Mar. 5	+41.0	+1.71	4	1	+2.80
Mar. 6	+93.2	+3.88	5	1	+3.33
Mar. 7	+66.6	+2.78	6	1	+2.64
Mar. 8	+59.7	+2.49			
Mar. 9	-193.3	-8.05			
Mar. 10	-202.2	-8.43			
Mar. 11	-206.6	-8.61	7	4	-6.31
Mar. 12	-68.0	-2.83			
Mar. 13	+1.3	+.05	8	2	-1.29
Mar. 14	-58.6	-2.44			
Mar. 15	-53.1	-2.21	9	2	-2.16
Mar. 16	-42.3	-1.76			
Mar. 17	-14.5	-.60	10	2	-1.48
Mar. 18	-70.9	-2.95			
Mar. 19	-154.8	-6.45	11	2	-6.11
Mar. 20	-205.6	-8.57			
Mar. 21	-277.5	-11.56	12	2	-10.53
Mar. 22	-249.9	-10.41			
Mar. 23	-256.1	-10.67	13	2	-10.90
Mar. 24	-283.9	-11.83			

.6 Constants

The following constants are used in the simulation:

k - conductivity of ice - 2.18 Joule-m/m^2Hr.°C

L - latent heat of fusion (ice) - 334000 Joule/kg

G - density of ice - 916 kg/m^3

.7 Theoretical Approach

The simultaneous effects of ice growth (from ambient freezing conditions) and ice deterioration (from bubbler) are expressed by:

$$db/dt = (q_2 - q_1)/LG$$

where:

$$q_1 = H\ (T_{water} - T_{ice})$$

H - Heat transfer coefficient at interface between ice and water (see .3 above)

T_{ice} - Temp. of ice at interface = 0°C

and:

$$q_2 = k\ (T_{water} - T_{air})/l_{ice}$$

k - Thermal conductivity of ice = 2.18 Joule-m/m^2 Hr °C

T_{ice} - Ambient air temp.

l_{ice} - Ice Thickness

.8 Example Using Station 17

At Station 17 for the period between Feb. 28 to Mar. 3, the following parameters are noted:

l_{ice} = 737 mm = .737 m

H = 460 Joules/m^2 s °C

T_{water} = .35°C

T_{ice} = 0°C

T_{air} = 7.36°C

q_1 = 460(.5-0) = 230 Joules/m^2s

q_2 = 2.18(0-(-7.36))/.737 = 22 Joules/m^2s

Therefore the rate of ice growth is:

$$\frac{db}{dt} = \frac{22 - 230}{334000 \times 916} = -6.799 \times 10^{-7} \text{ m/s}$$

$$= 59 \text{ mm/day}$$

(The negative sign denotes thawing) the actual measured value of deterioration for this period is:

737 - 711 = 26 mm/day

The % difference between the calculated and actual resultant thicknesses is:

$$\frac{711 - (737-58)}{711} \times 100\% = 4.501\%$$

2.3.4 Bubbler Performance - Using the Programme

When a run is initiated the computer requests inputs for Station Number, Heat Transfer Coefficient and Number of Periods in simple question/answer format.

Following this, values for Period Durations, Average Temperature Per Period and Measured Ice Thicknesses are requested in column format.

A complete table of calculated and actual ice thicknesses and deterioration rates with percentage differences is output, showing the predicted performance of the bubbler at the station in question.

3. CONCLUSIONS

The performance of the conventional line bubbler and our ability to predict this performance have been correlated to accuracies of approximately 5%, excluding anomalies. This indicates that the line bubbler design and performance models, as well as their supporting theory, can be used to design a bubbler system for a harbour slip, and to specifically predict how the system will extend the shipping season.

The rakes, although not effective during this trial, warrant another test. They have proven to be effective at Thunder Bay Terminals and, providing that their test is limited to outshore and that the volume of air to the rakes can be increased (which approximately duplicates their operating condition at Thunder Bay Terminals), they should be made to perform well at this location also.

Other technologies should also be tried to complement the proven line bubbler.

4. REFERENCES

1. Air Bubbler Systems to Suppress Ice. U. S. Army Cold Regions Research and Engineering Laboratory. Ashton, G. D. September, 1974.

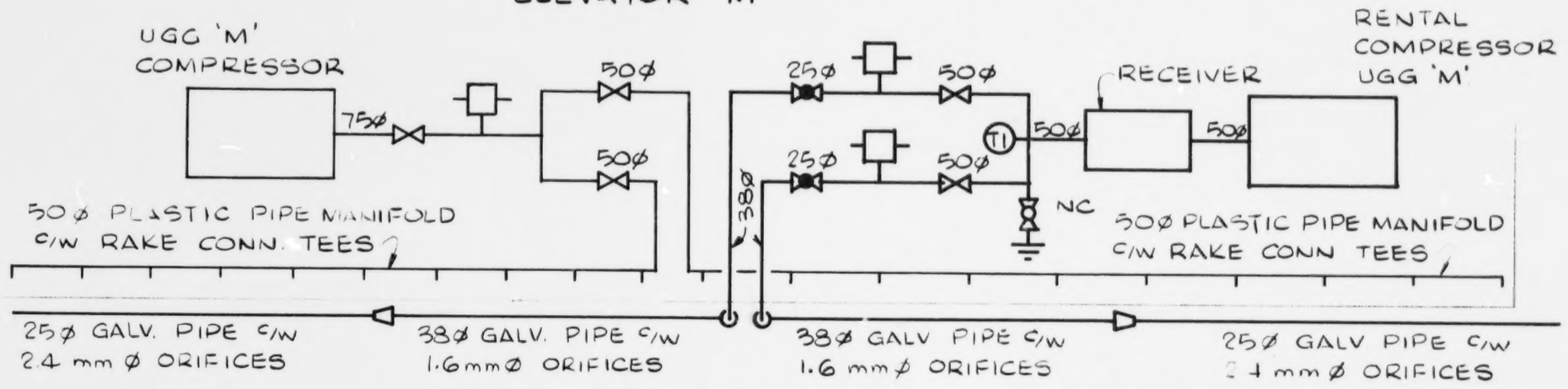
2. TP-2657 Air Bubbler Ice Control Experiment in Thunder Bay. Hill, J. E., P. Eng., May, 1980.

3. TP-3797E Air Bubbler Ice Control Experiment in Thunder Bay, Ontario. Kamo, H. R., Nelson, D.A., May, 1982.

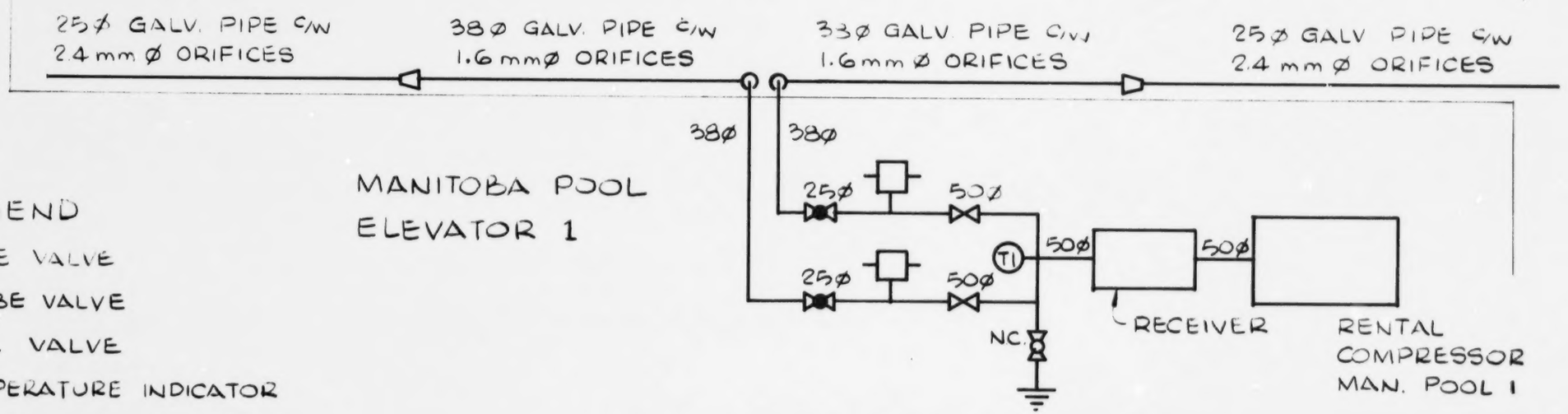
4. TP-1174C Field Temperature Measurement in Thunder Bay Harbour. Winter 1983. Abdelnour, R., Nisbett, V., April, 1983.

5. DRAWINGS, PHOTOGRAPHS AND COMPUTER PRINTOUTS

UNITED GRAIN GROWERS
ELEVATOR 'M'



INSHORE DIFFUSERS — SLIP — OUTSHORE DIFFUSERS



MANITOBA POOL
ELEVATOR 1

LEGEND

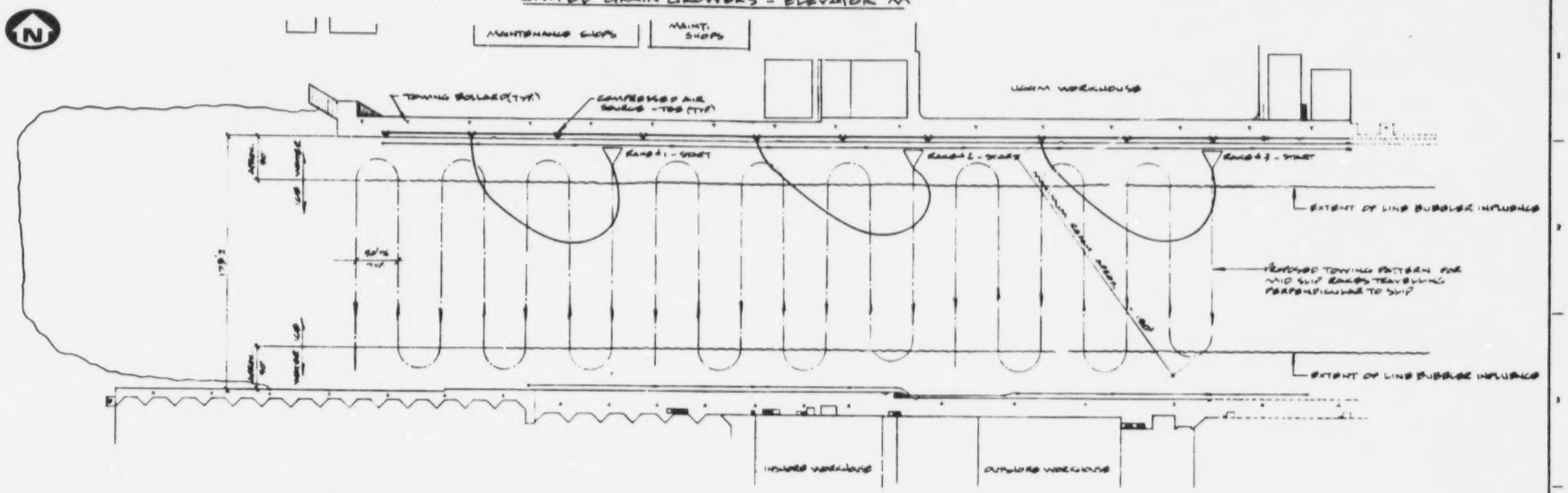
- GATE VALVE
- GLOBE VALVE
- BALL VALVE
- TI — TEMPERATURE INDICATOR
- ANNUBAR FLOW METER
- TO DRAIN
- NC — NORMALLY CLOSED

VB COOK CO. LIMITED
CONSULTING ENGINEERS
THUNDER BAY, ONTARIO

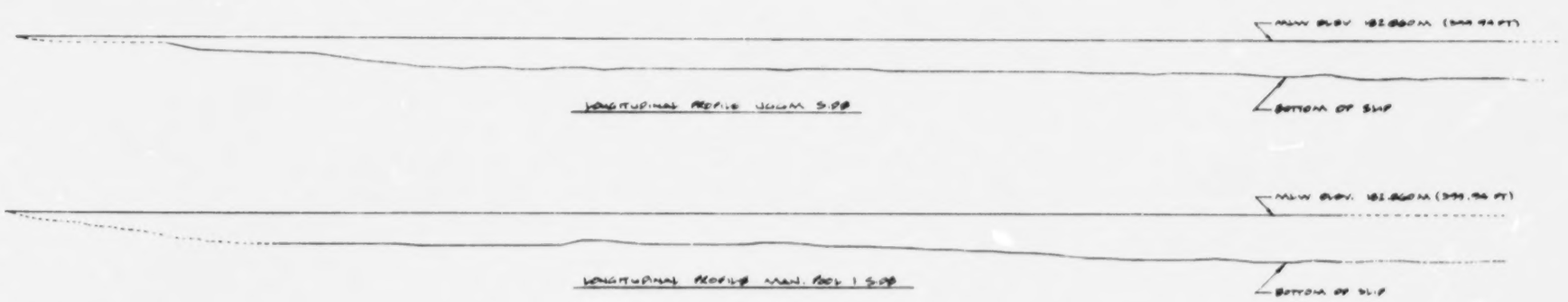
BUBBLER SYSTEM FLOW DIAGRAM
UGG 'M' - MAN. POOL 1 - SLIP

DRN	AS	CHKD		SCALE	NTS	DWG NO
APP		DATE	83-6	PROJ NO	8214401	500

UNITED GRAIN GROWERS - ELEVATOR M


MAINTENANCE SHOPS
MAINT. SHOPS
TOWING BOLLARD (TYP.)
COMPRESSED AIR SOURCE - TOP (TYP.)
UGRM WAREHOUSE
RAKE 1 - START
RAKE 2 - START
RAKE 3 - START
EXTENT OF LINE BUBBLER INFLUENCE
PROPOSED TOWING PATTERN FOR MID SLIP RAKES TRAVELLING PERPENDICULAR TO SLIP
EXTENT OF LINE BUBBLER INFLUENCE
INSIDE WAREHOUSE
OUTSIDE WAREHOUSE

MANITOBA POOL 1



LONGITUDINAL PROFILE UGRM S.SB

LONGITUDINAL PROFILE MAN. POOL 1 S.SB

NOTES:

- FOR DETAILS OF MIDSLIP DIFFUSERS (RAKES) SEE DRAWING # 307
- AIR CAPACITY PER RAKE - 36 SCFM

BILL OF MATERIALS

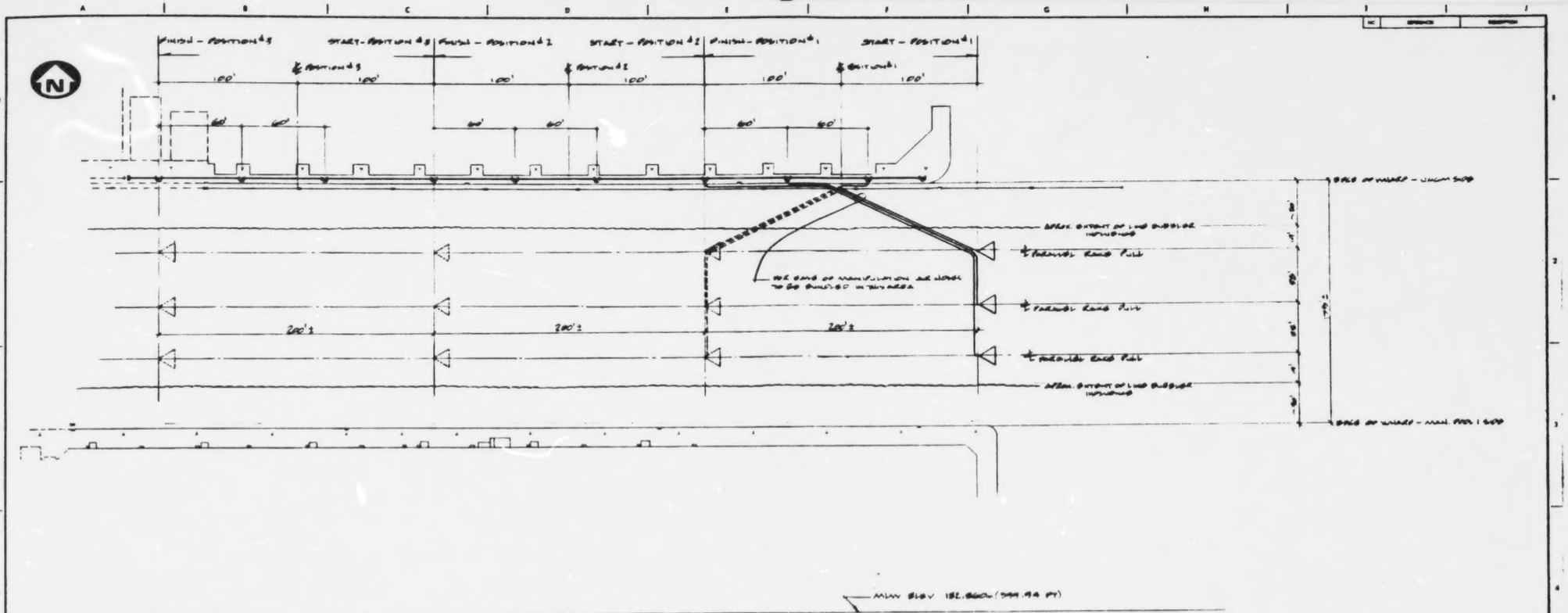
ITEM	REQ'D	DESCRIPTION
1	3 ea	95 c.f.m. 100 PSI COMPRESSOR HOSE
2	1000 FT	3/8" ø NYLON ROPE

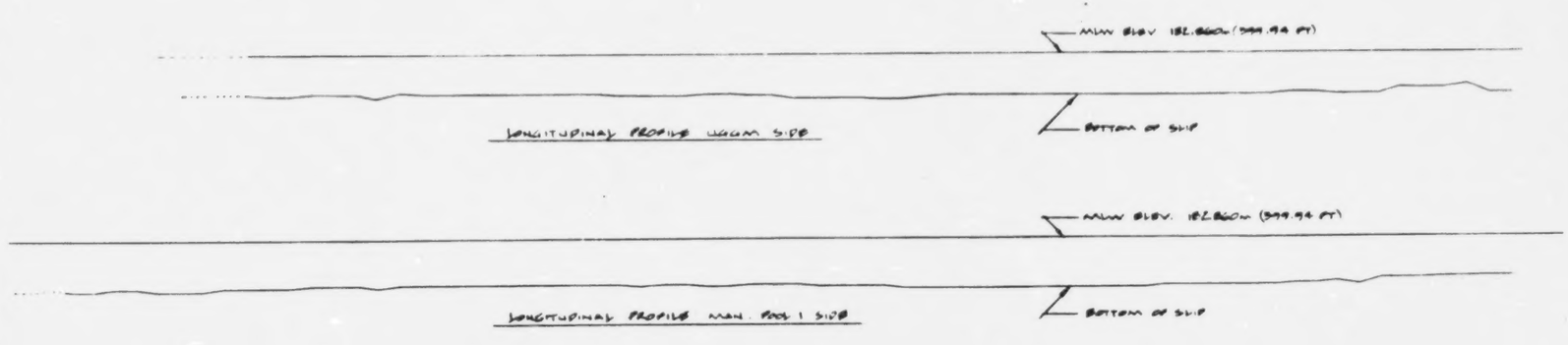
REVISED ORIENTATION OF PROPOSED REGULAR MID-SLIP RAKES

AIR BUBBLER MONITORING FOR LAKEHEAD HARBOUR COMMISSION
THUNDER BAY ONTARIO

DATE OCT. 82
DRAWN RG GIBBINS
DES. T.A.M.
CHKD
APP.
PROJ. NO. 82-144-101
DWG. NO. 301
REV. NO.

© COCK CO LIMITED CONSULTING ENGINEERS THUNDER BAY ONTARIO


FINISH - POSITION #5
START - POSITION #5
FINISH - POSITION #2
START - POSITION #2
FINISH - POSITION #1
START - POSITION #1
100'
60'
200'±
MAX. EXTENT OF LAND DISPOSAL IMPOUNDMENT
± RACK #3 RISER PIPE
± RACK #2 RISER PIPE
± RACK #1 RISER PIPE
MIN. EXTENT OF LAND DISPOSAL IMPOUNDMENT
DEPTH OF WATER - LOCUM SLIP
DEPTH OF WATER - MAIN PIER 1 SLIP
NO ZONE OF MANIPULATION OR WORK TO BE DEVELOPED IN THIS AREA


MLW ELEV. 182.860m (599.94 FT)
BOTTOM OF SLIP
LONGITUDINAL PROFILE LOCUM SLIP
MLW ELEV. 182.860m (599.94 FT)
BOTTOM OF SLIP
LONGITUDINAL PROFILE MAIN PIER 1 SLIP

NOTES:

- FOR DETAILS OF MID-SLIP DIFFUSERS (RACKS) SEE DWG # 501
- AIR CAPACITY PER RACK - 96 SCFM

BILL OF MATERIALS

ITEM	NO. REQ'D	DESCRIPTION
1	160 FT	50 ø VOITH CONTROLOR HOSE
2	180 FT	— DITTO —
3	830 FT	— DITTO —
4	1260 FT	50 ø NYLON ROPE

METRES
100 90 80 70 60 50 40 30 20 10 0 100

FEET
300 15 0 30 60 90 120 150 180 210

PROPOSED OPERATION OF RACKS MID-SLIP RACKS

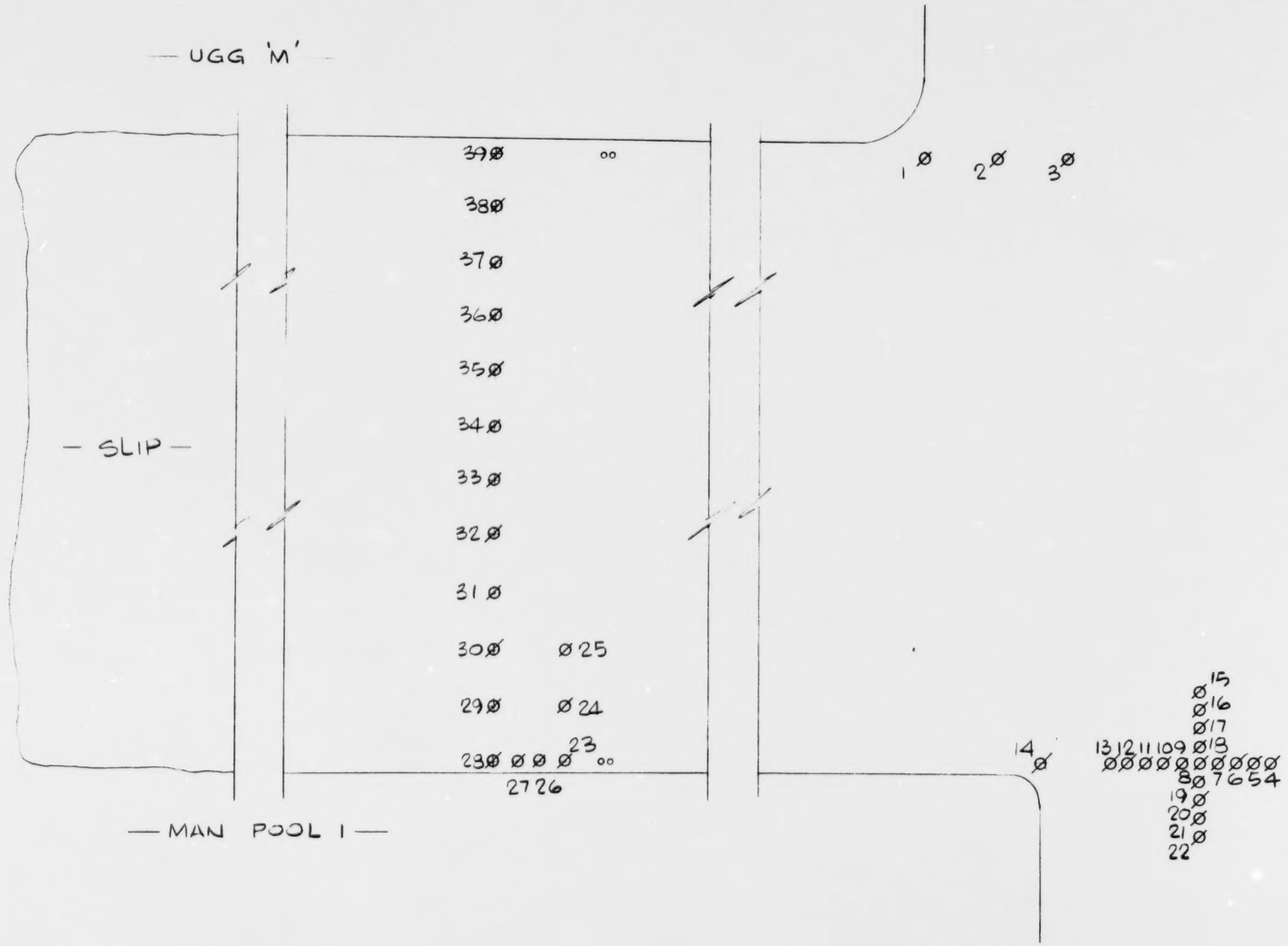
AIR BUBBLER MONITORING FOR LAKEHEAD HARBOUR COMMISSION
THUNDER BAY ONTARIO

PROJ. NO. 82-149-01

DWG. NO. 502

REV. NO. 2

V.G. COOK CO. LIMITED
CONSULTING ENGINEERS
THUNDER BAY ONTARIO



VB COOK CO. LIMITED
CONSULTING ENGINEERS
THUNDER BAY, ONTARIO

PLAN FOR ICE METERING STATIONS - UGG M & MAN POOL 1

DRN	AS	CHKD		SCALE	NTS	DWG NO
APP		DATE		PROJ NO	8214401	503

DATE \ STATION	1	2	3	4	5	6	7	8	9	10	11 ✓	12	13	14	15	16	17 ✓	18	19	20	21 ✓	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
FEB. 20 CONTROL	610	635	673	635	686	686	711	686	686	699	737	749	660	889	711	737	737	737	737	737	737	737	584	787	762	610	660	584	787	762	749	749	724	724	711	686	660	610	610
MAR. 3	—	584	660	584	660	686	737	673	673	673	699	711	610	838	686	711	711	673	686	711	686	711	483	749	762	584	559	406	-62	775	749	737	737	737	711	686	673	572	533
4	—	572	648	ϕ	648	673	673	673	673	673	686	686	ϕ	775	686	673	673	660	686	711	686	711	ϕ	749	762	533	559	ϕ	737	775	749	737	737	737	711	660	673	533	483
5	—	572	546	ϕ	533	584	648	635	622	660	673	673	ϕ	686	686	648	610	584	660	673	673	711	ϕ	686	749	495	483	ϕ	711	749	737	737	737	724	686	610	648	508	432
6	—	445	508	ϕ	ϕ	445	584	584	597	583	635	610	ϕ	584	584	521	533	584	635	648	635	686	ϕ	584	711	457	432	ϕ	610	572	711	737	737	711	673	483	572	470	ϕ
7	—	432	508	ϕ	ϕ	368	559	559	533	508	546	508	ϕ	ϕ	533	483	432	419	559	648	622	622	ϕ	533	660	330	381	ϕ	559	686	686	711	673	686	597	432	572	432	ϕ
8	—	457	546	ϕ	ϕ	368	508	508	521	572	559	533	ϕ	ϕ	508	572	457	483	521	610	610	660	ϕ	584	711	406	330	ϕ	584	673	699	711	686	673	622	483	559	432	ϕ
10	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	ϕ	533	686	699	699	686	660	610	432	584	381	ϕ
12	—	305	406	ϕ	ϕ	267	394	432	483	521	521	432	ϕ	ϕ	470	508	419	419	508	572	584	685	ϕ	521	711	—	—	ϕ	559	673	699	711	686	673	610	394	533	356	ϕ
14	—	292	318	ϕ	ϕ	191	406	470	495	521	457	381	ϕ	ϕ	483	483	368	356	521	559	559	610	ϕ	597	711	381	343	ϕ	610	699	711	724	699	673	597	406	178	ϕ	ϕ
16	—	267	381	ϕ	ϕ	89	305	343	368	457	394	292	ϕ	ϕ	318	343	292	292	406	445	533	584	ϕ	546	686	305	267	ϕ	508	635	686	711	686	660	559	394	267	ϕ	ϕ
18	—	292	279	ϕ	ϕ	ϕ	165	254	394	419	330	178	ϕ	ϕ	267	229	216	216	394	457	508	533	ϕ	495	686	267	203	ϕ	457	597	635	699	686	660	584	406	406	ϕ	ϕ
20	—	—	—	ϕ	ϕ	ϕ	127	267	279	330	267	178	ϕ	ϕ	152	102	89	178	254	318	356	508	ϕ	406	635	—	—	ϕ	432	610	686	711	673	660	597	381	394	ϕ	ϕ
22	—	165	318	ϕ	ϕ	ϕ	140	292	330	330	305	178	ϕ	ϕ	191	191	178	140	267	343	457	559	ϕ	406	686	ϕ	ϕ	ϕ	356	572	686	711	699	673	610	419	445	76	ϕ
24	—	203	292	ϕ	ϕ	ϕ	140	241	318	343	292	191	ϕ	ϕ	229	216	165	140	254	305	381	546	ϕ	381	686	ϕ	ϕ	ϕ	356	584	686	737	711	660	737	406	406	76	ϕ

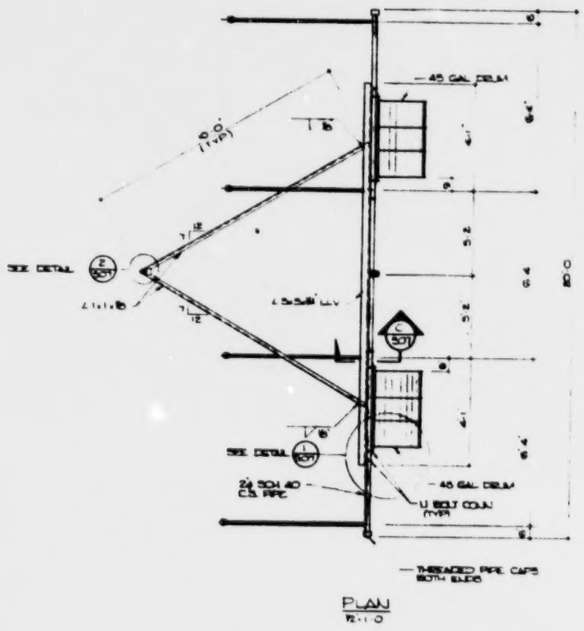
— ICE THICKNESSES IN MM

LAKEHEAD HARBOUR COMM'N

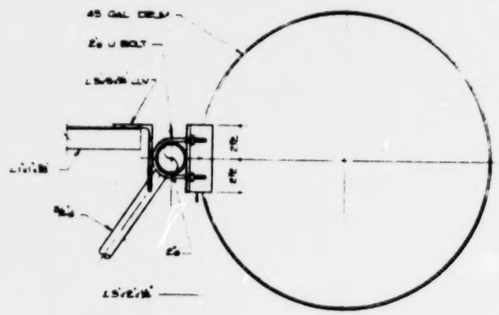
V.B. COOK CO. LIMITED
CONSULTING ENGINEERS
THUNDER BAY, ONTARIO

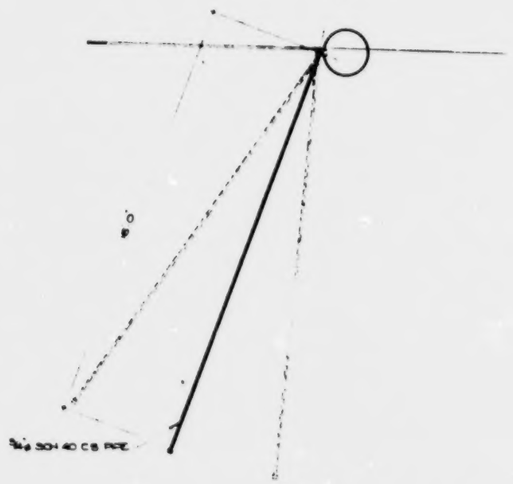
AIR BUBBLER MONITORING
1982/83

DRN	RK	CHKD	—	SCALE	NTS	DWG Nº
APP	—	DATE	July 83	PROJ Nº	82-144	F504

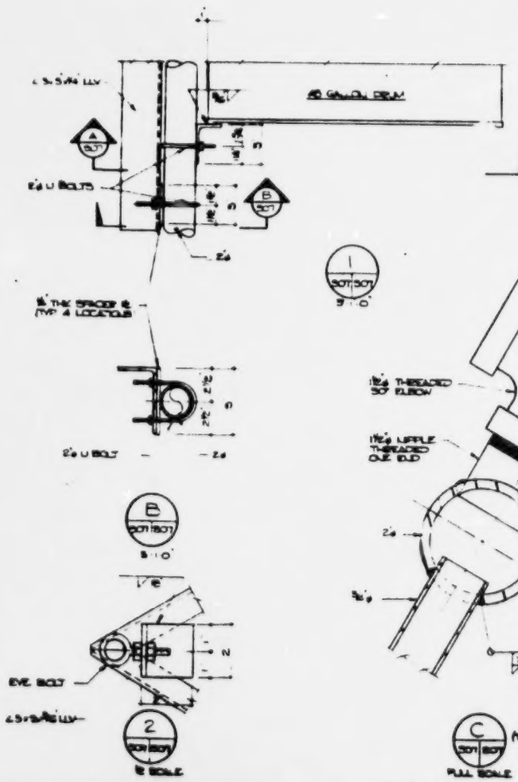


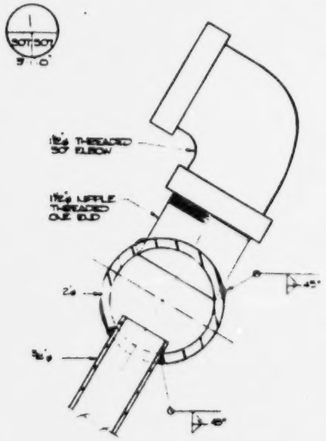
PLAN





ELEVATION





NOTE
APPROX WEIGHT 1200 LBS

MID SLIP DIFFUSERS
FLOATING SUPPORT PLATFORM

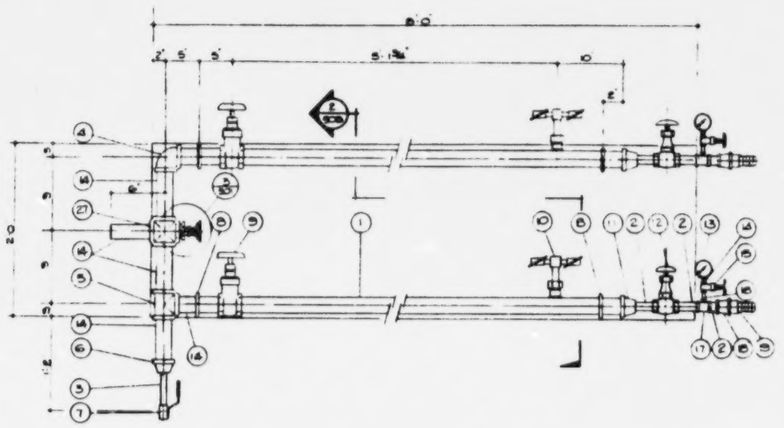
JAMESTOWN HARBOUR COMMISSION
RESCUE ICE BREAKING PROGRAMME

W COOK CO LIMITED

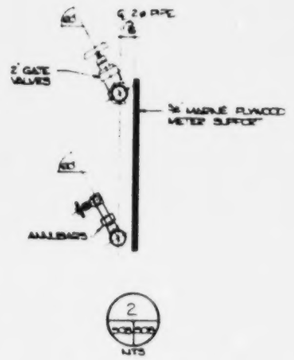
FROM NO
RE-164-01

DWG NO
307

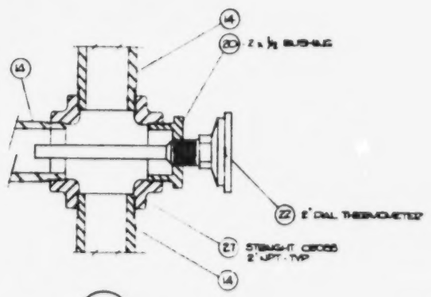
REV NO



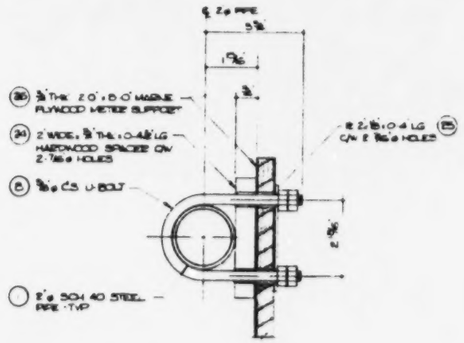
1 — AIR METERING STATION — NTS
NOTE: 2" GATE VALVE AND ANALOG SHOWN IN VERTICAL FLANGE. FOR ACTUAL POSITION SEE DET 2



2 — NTS



3 — NTS


3/4" THK 2'-0" x 8'-0" MARINE PLYWOOD METER SUPPORT
2 WIDE, 3/4" THK x 10-4 1/2" LG HARDWOOD SPACERS ON 2-7/16 ø HOLES
3/8 ø CS U-BOLT
2 ø SCH 40 STEEL PIPE - TYP
2 x 15-0 x 4 LG CAN 2 7/16 ø HOLES

4 — 1/2 FULL SCALE

BILL OF MATERIAL - FOR TWO METERING STATIONS

MARK NO.	ITEM NO.	ASSY GROUP	DESCRIPTION	REMARKS
–	1	–	2" ø SCHEDULE 40 STEEL PIPE	
–	2	–	1" ø SCHEDULE 40 STEEL PIPE	
–	3	–	1/2 ø SCHEDULE 40 STEEL PIPE	
1	4	1	2 NPT CLASS 125 STANDARD ELBOW	
2	5	O	2 NPT CLASS 125 STANDARD BLACK TEE	
O	6	1	2 x 1/2 NPT CLASS 125 STANDARD BLACK CONCENTRIC RED	
1	7	1	1/2 NPT HORIZONTAL 600 SCREWED END BALL VALVE W/ SS 4 & 2	
8	8	O	3/8 x 2 FIG 137 CS U BOLT - GRAINGER	3/8 LG THREAD
4	9	O	2 NPT 125 # BRONZE GATE VALVE FIG 300 JENKINS	
4	10	O	ANALOG MODEL AMP 75 2 SCHED 40 CZ 036	
4	11	O	2 x 1 NPT CLASS 125 STANDARD BLACK CONCENTRIC RED	
O	12	4	1" JENKINS BRONZE VALVE #48 FIG 300	
O	13	4	1/2 NPT MARSH PRESSURE GAUGE - J1452, 2 DIAL, 1/2 CONN GRAD 0-30	
5	14	5	2 NPT NIPPLE SCH 40 STEEL PIPE	
O	15	4	1/2 NPT 125# BRONZE GATE VALVE FIG 300 JENKINS	
O	16	4	1/2 ø SCHEDULE 40 STEEL PIPE	
O	17	4	1 x 1 x 1/2 CLASS 125 NPT REDUCING TEE	
O	18	4	1/2 x 1 NPT REDUCER - PIE EQUIVALENT	
O	19	4	1/2 x 1 DISCHARGE HOSE NIPPLE VALVE NPT-PIE EQUIVALENT	
O	20	2	2 x 3/4 NPT CLASS 125 STANDARD BLACK HEX BUSHING	
–	21	–	DELETED	
1	22	1	[illegible] STEM 1/2 NPT	
–	23	–	DELETED	
–	24	8	2 x 3/4 x 10-4 1/2 LG HARDWOOD SPACERS CAN 2-7/16 ø HOLES	
–	25	8	1/4 2 x 15 x 10-4 LG CAN 2 7/16 ø HOLES	
–	26	2	3/4 THK 2'-0" x 8'-0" MARINE PLYWOOD	
–	27	2	2 NPT CLASS 125 STANDARD BLACK CROSS	

MARK	DATE	BY	GENERAL REVISION	CK

AIR METERING STATION

LAKE ERIE MANAGEMENT COMMISSION
GREAT LAKES COAL BURNING PROGRAMME

THUNDER BAY ONTARIO

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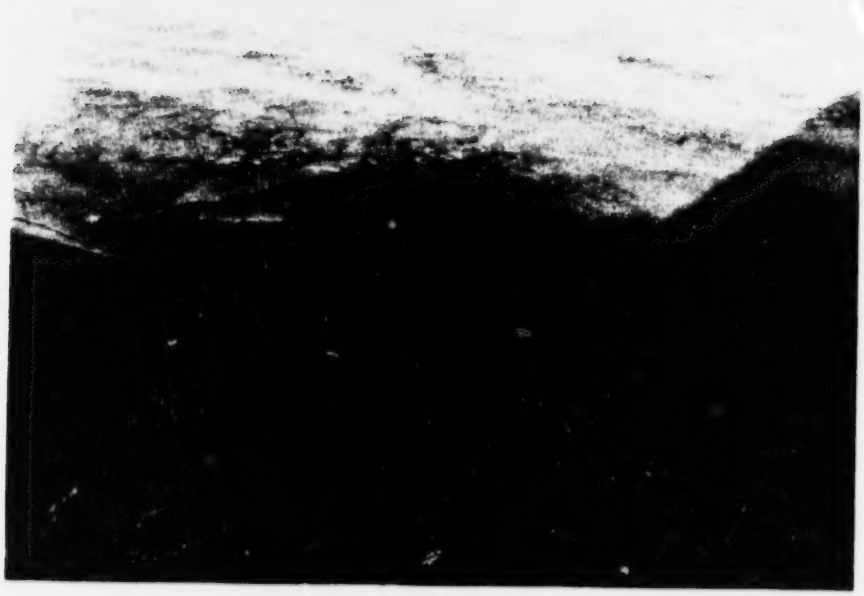
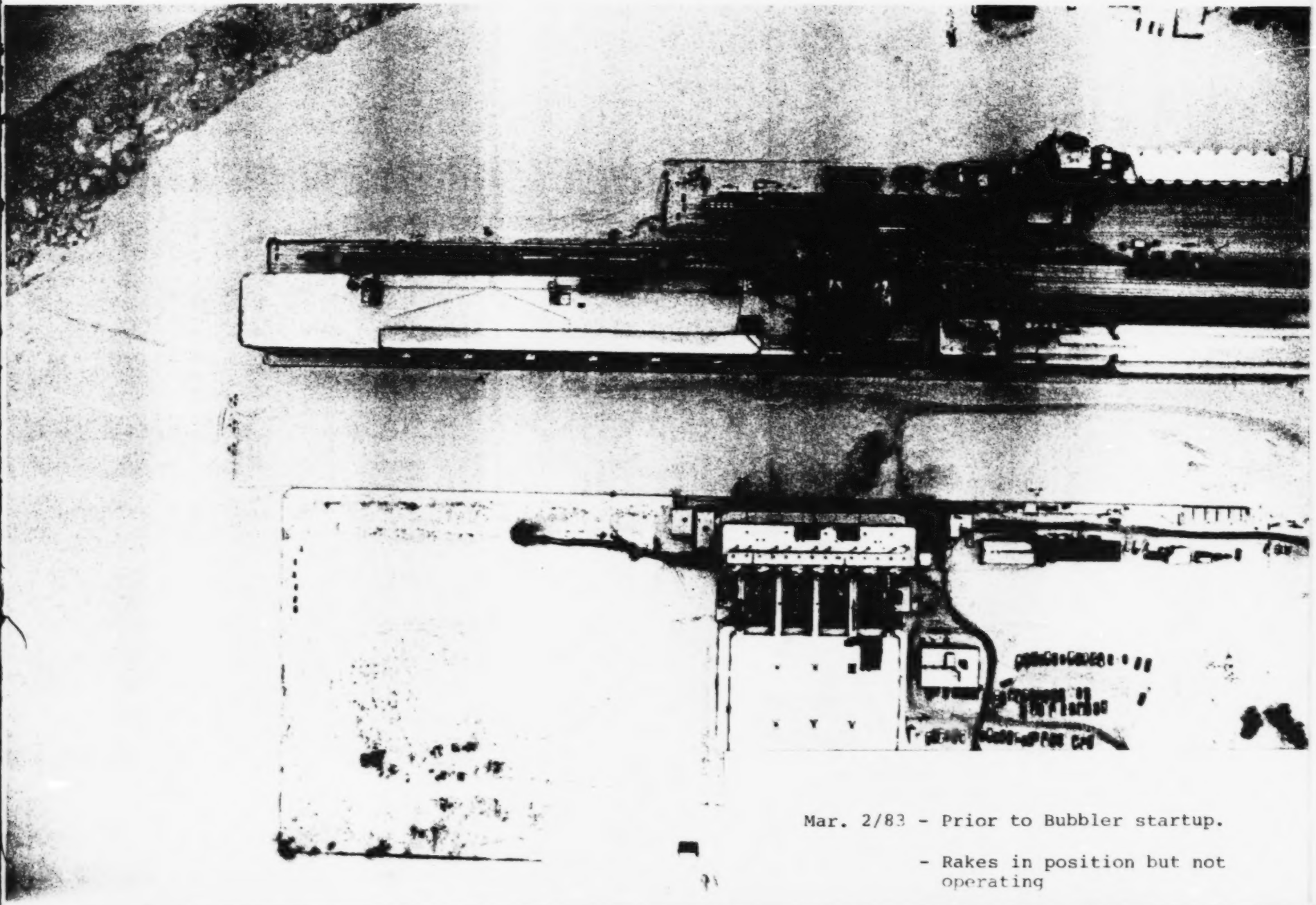
CONSULTING ENGINEERS
THUNDER BAY ONTARIO

DRN
CHK
APP
ITEM NO.
SDP-144-O
DWG NO.
305
REV NO.
A

Mid-Slip Diffuser (Rake) Propogation Test

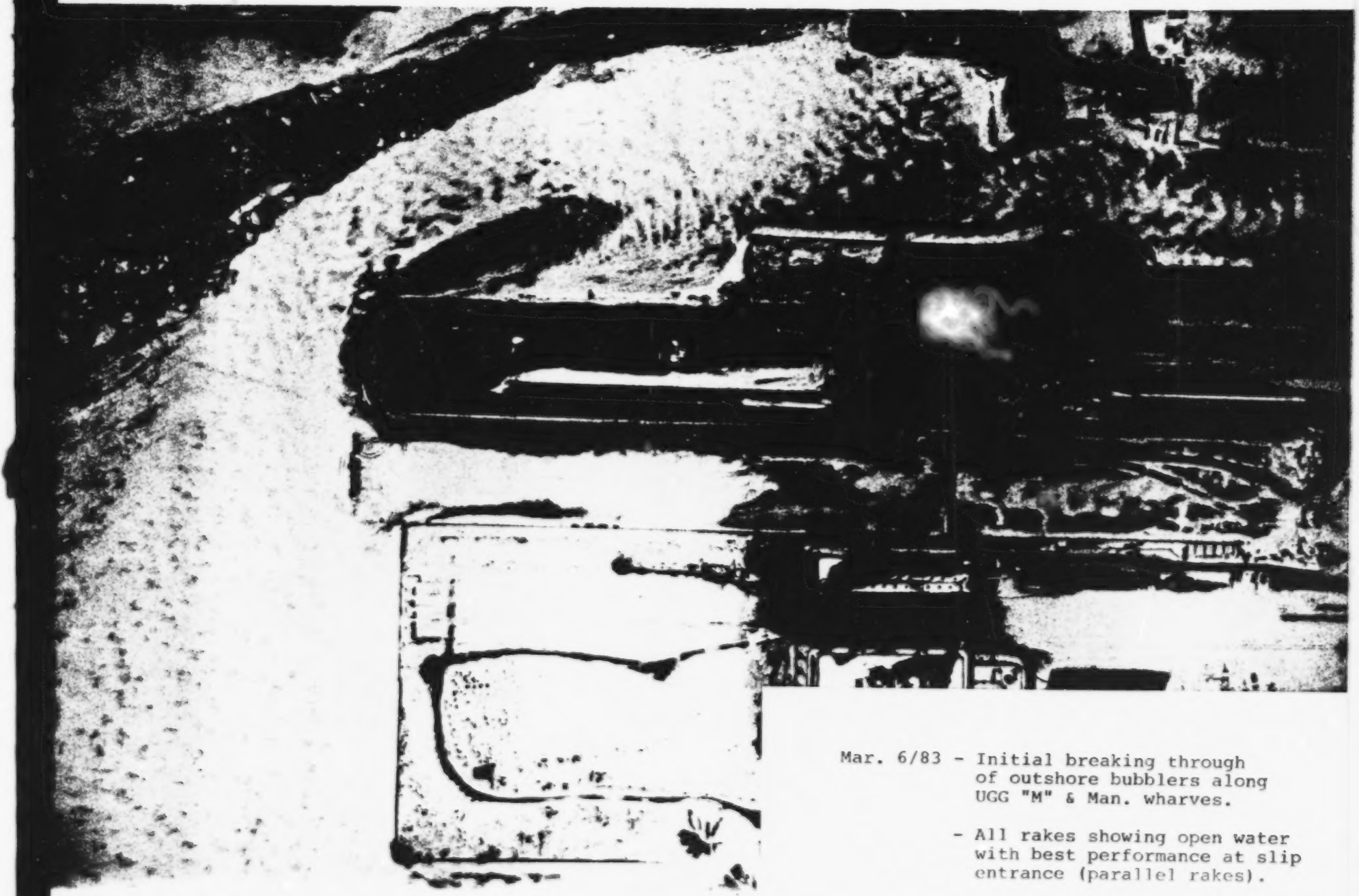


Parallel Rakes in Operation



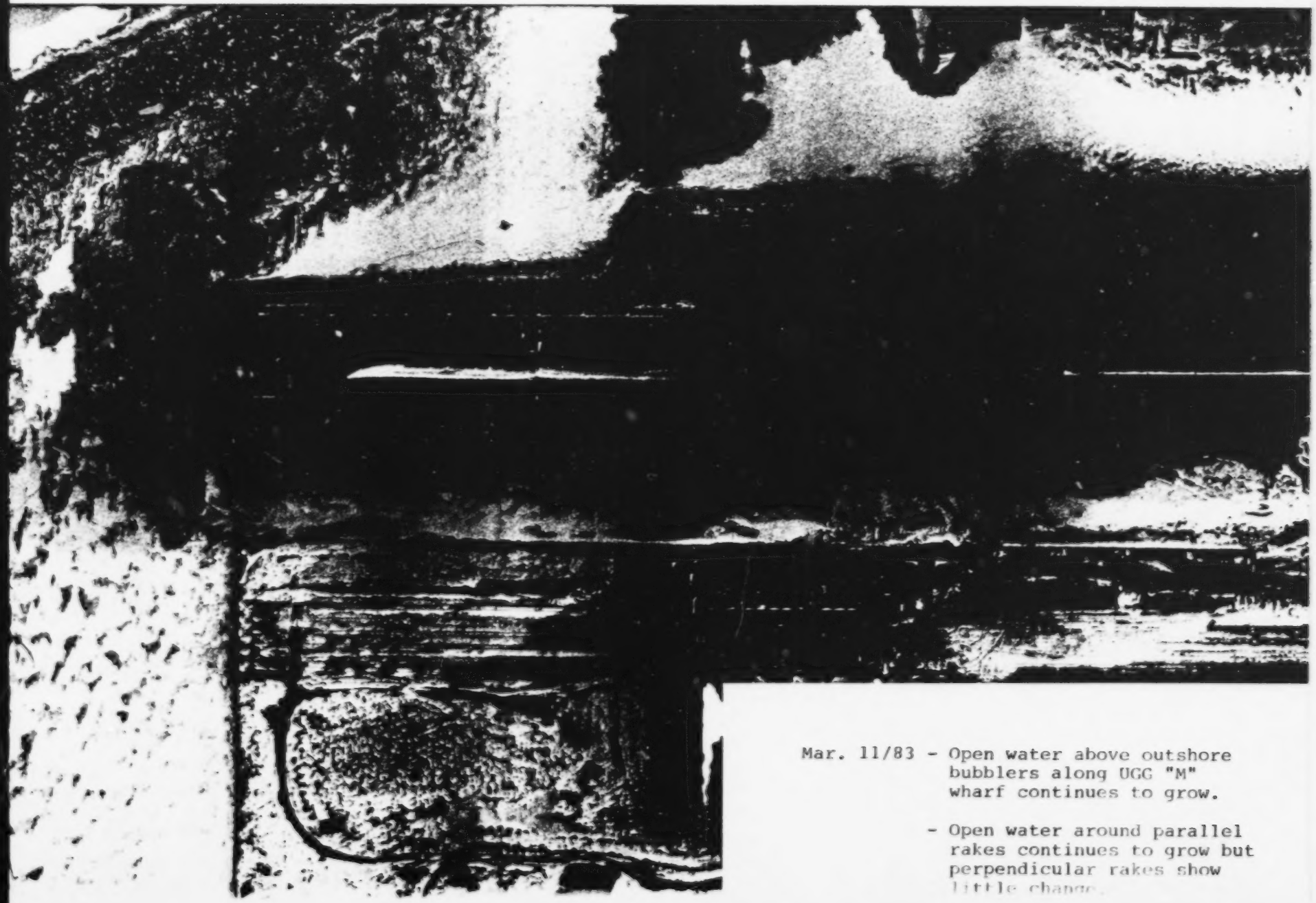
Mar. 2/83 - Prior to Bubbler startup.

- Rakes in position but not operating



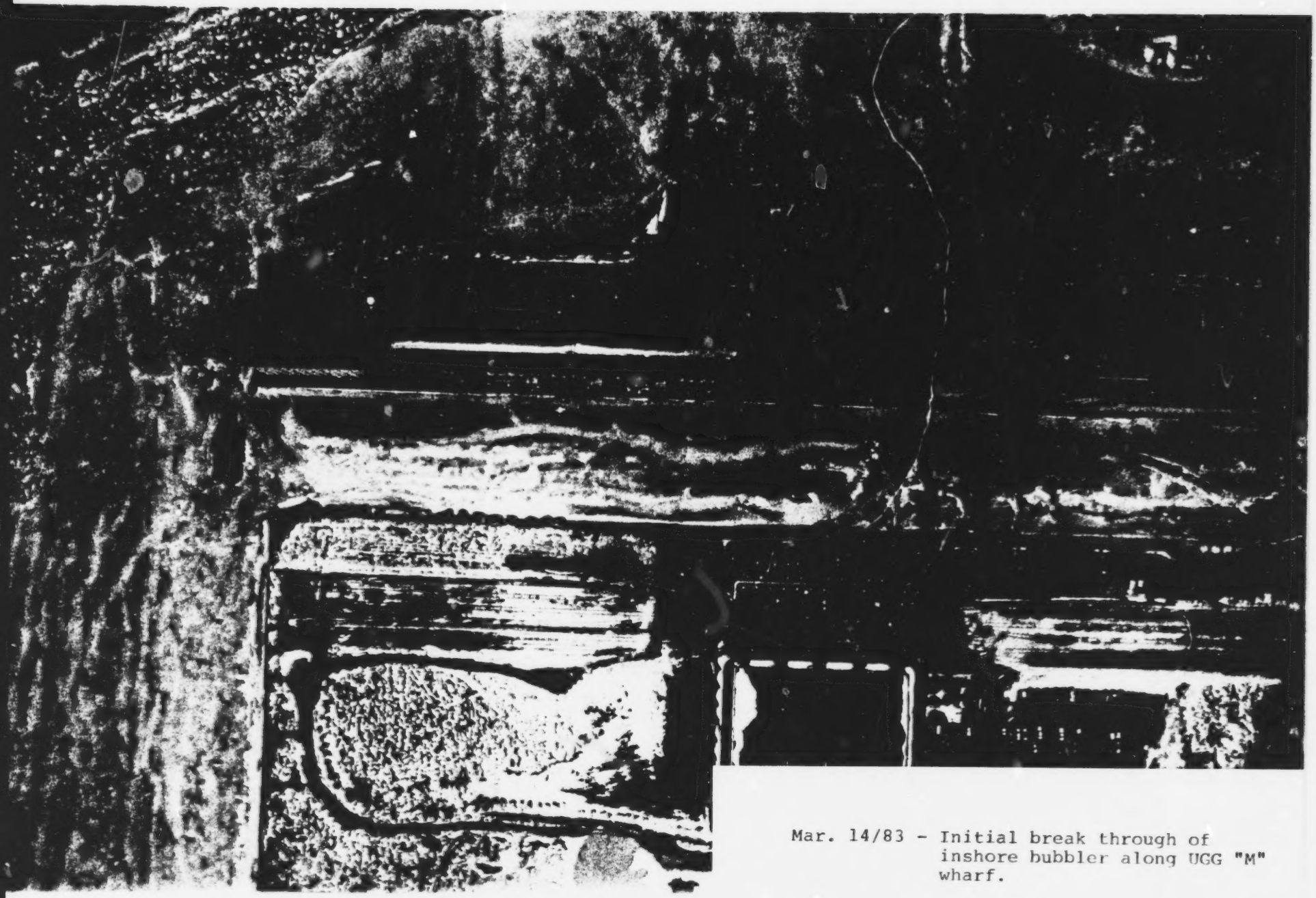
Mar. 6/83 - Initial breaking through of outshore bubblers along UGG "M" & Man. wharves.

- All rakes showing open water with best performance at slip entrance (parallel rakes).

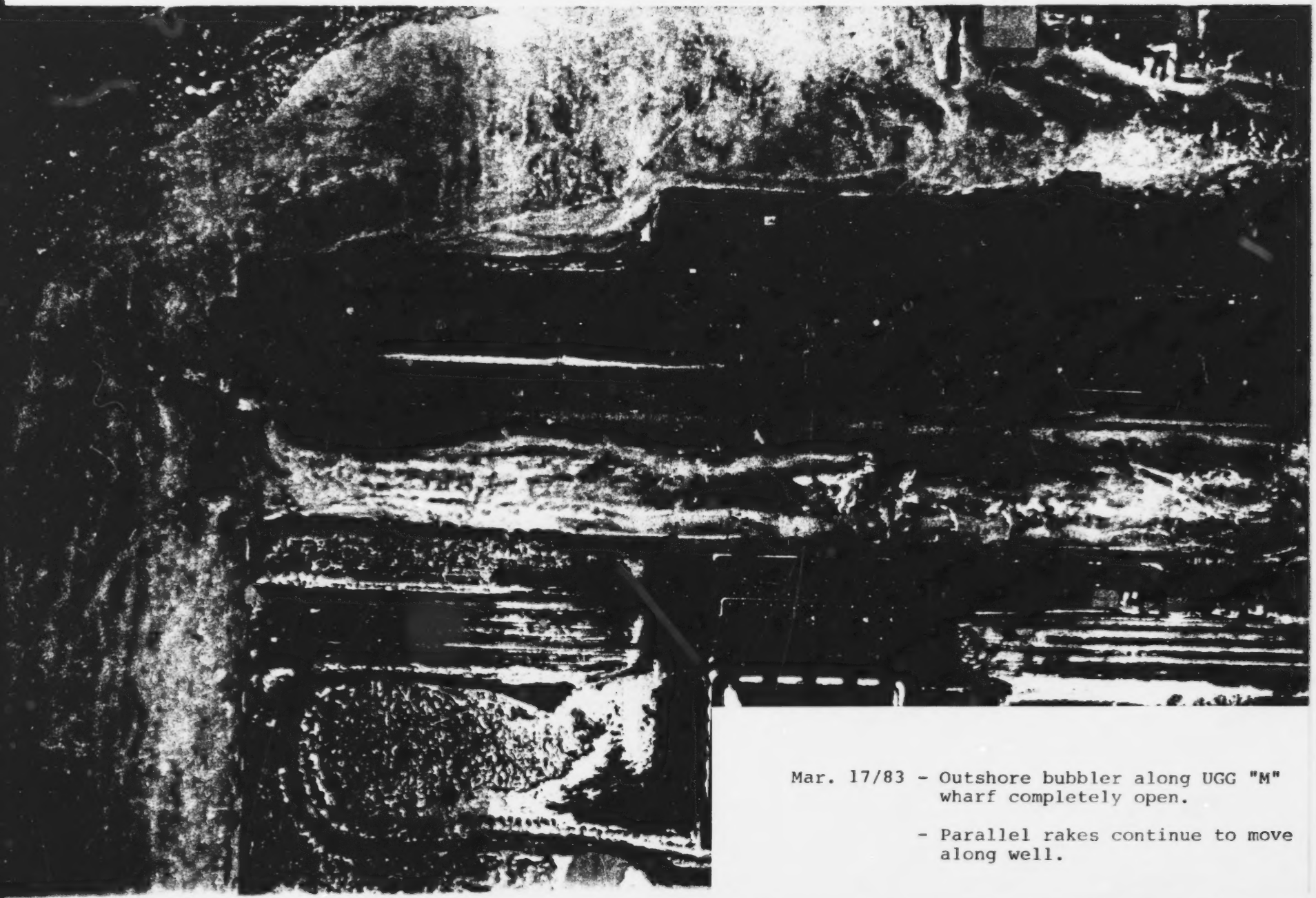


Mar. 11/83 - Open water above outshore bubblers along UGC "M" wharf continues to grow.

- Open water around parallel rakes continues to grow but perpendicular rakes show little change.

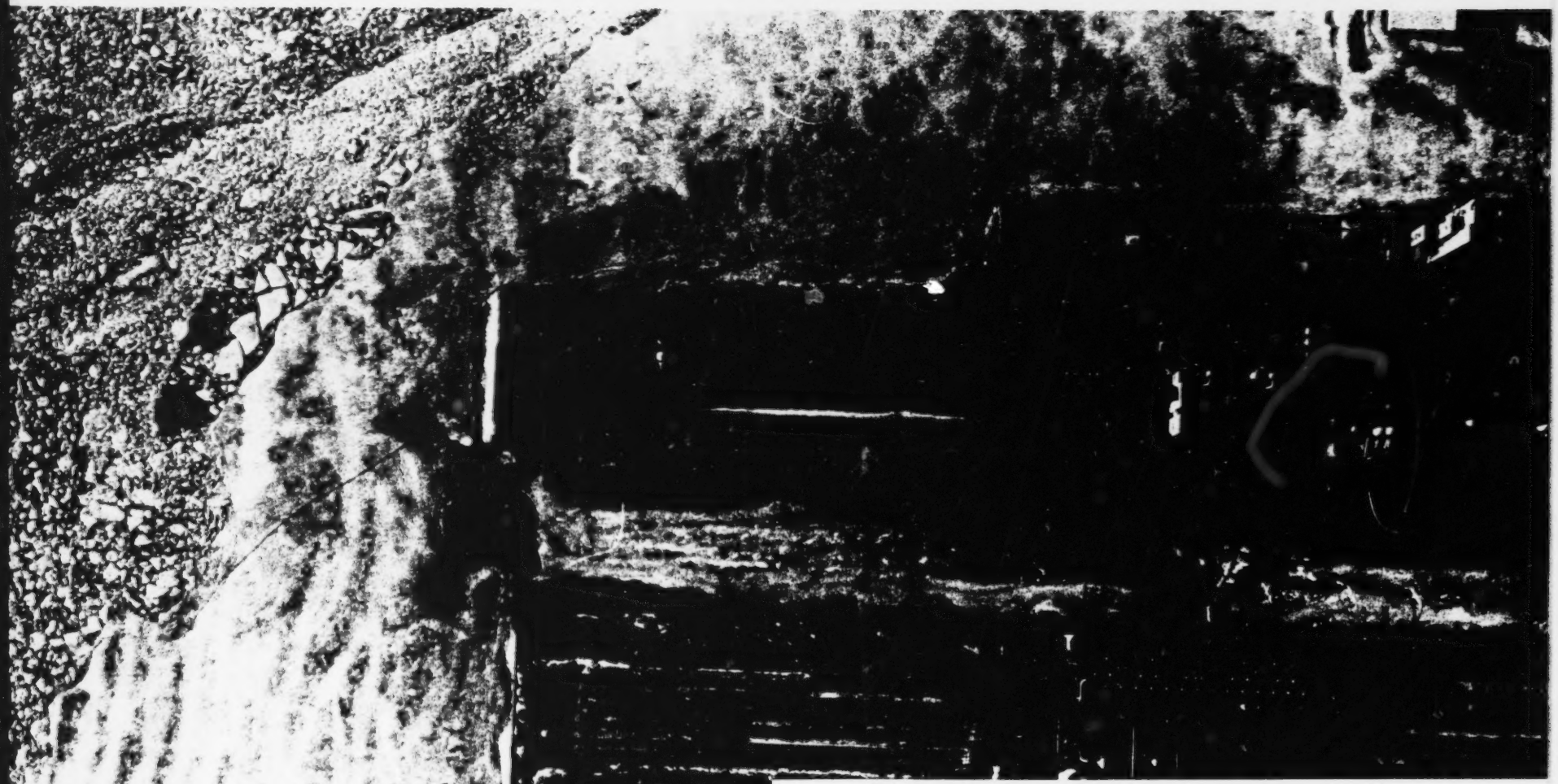


Mar. 14/83 - Initial break through of inshore bubbler along UGG "M" wharf.



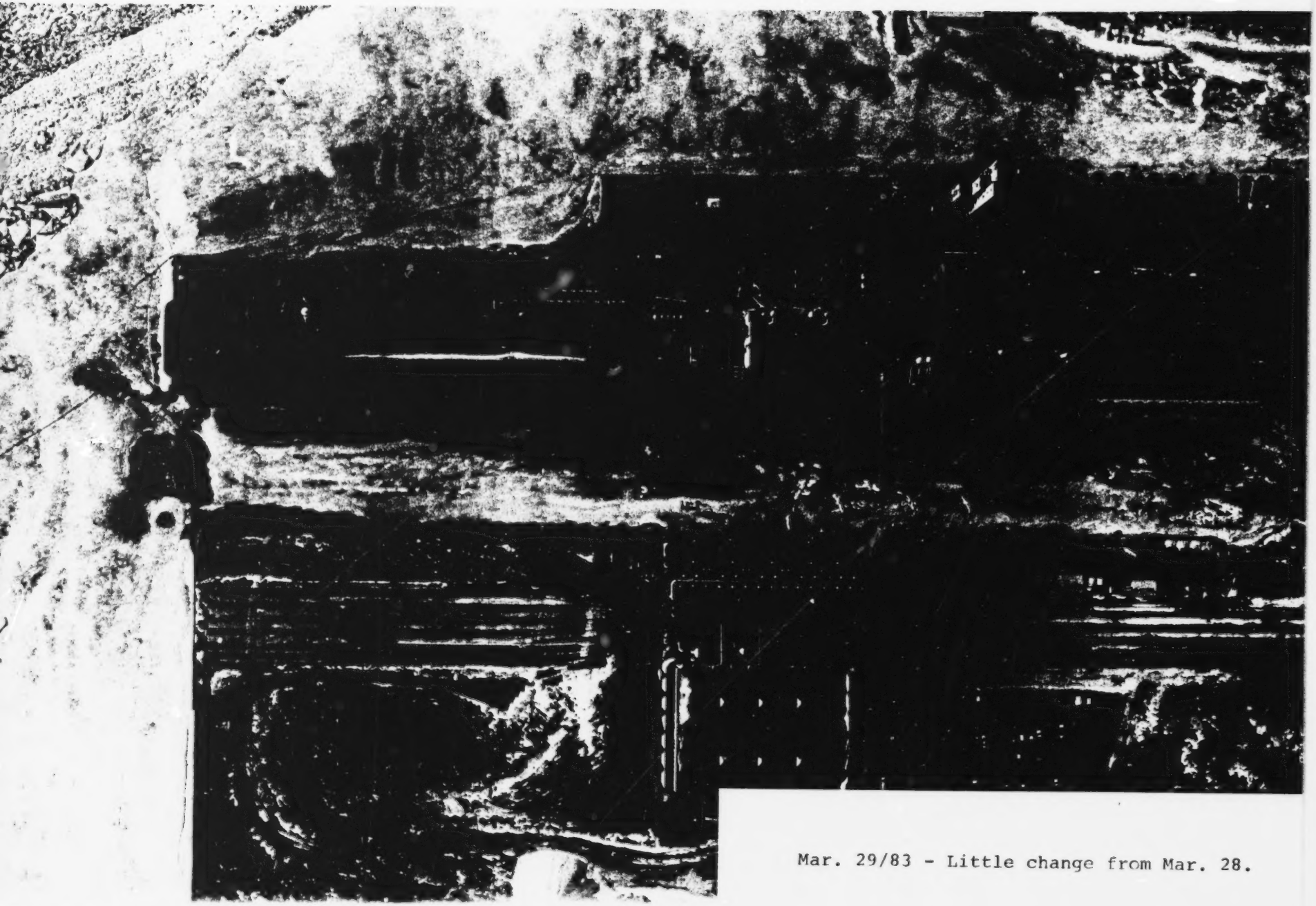
Mar. 17/83 - Outshore bubbler along UGG "M" wharf completely open.

- Parallel rakes continue to move along well.

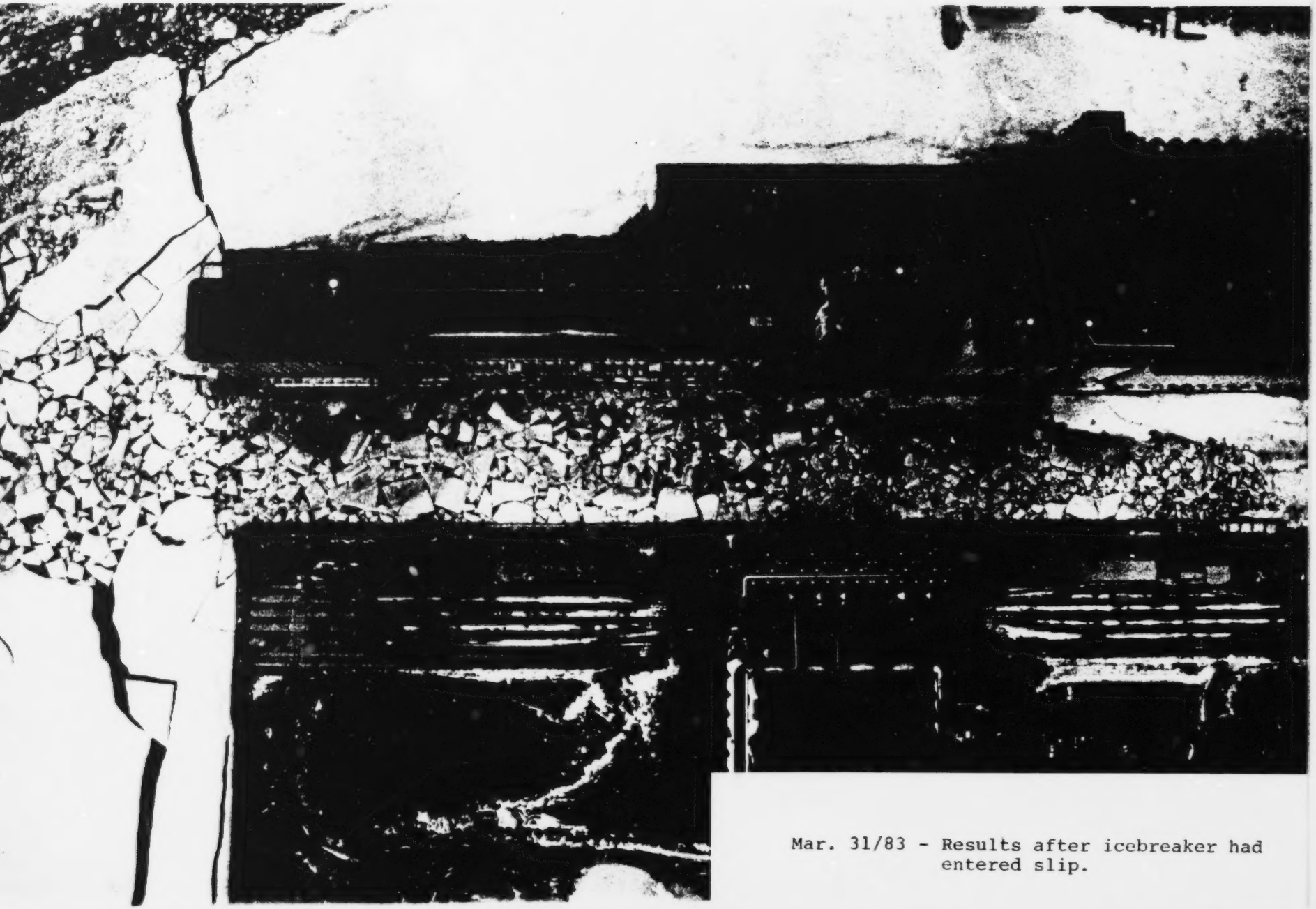


Mar. 28/83 - Open water above bubblers continues to grow with air bubbles visible on open water surface.

- Parallel rakes continue to make good progress.



Mar. 29/83 - Little change from Mar. 28.



Mar. 31/83 - Results after icebreaker had entered slip.

```
90 REM ********************************************** HEADER
100 CLS:C=0
110 LPRINT"          ************************************************************"
120 LPRINT:LPRINT"                                L.H.C. BUBBLER SYSTEM STUDY":LPRINT
130 LPRINT"          ************************************************************":FOR I=1TO3:PRINT:NEXT I
140 LPRINT"                    MODEL FOR THE OPTIMIZATION OF BUBBLER"
141 LPRINT"                    PARAMETERS ALONG DIFFUSER SECTIONS"
145 LPRINT:FOR I=1TO2000:NEXT I
150 REM ********************************************* LIMITATIONS
160 LPRINT:LPRINT"THE FOLLOWING LIMITATIONS APPLY :":LPRINT
170 LPRINT"THE MODEL REPRESENTS A TWO SECTION DIFFUSER"
190 LPRINT"K=1.4 ( POLYTROPIC INDEX OF COMPRESSION )":K=1.4
200 LPRINT"G=32.2 FT/SEC2 ( ACCELERATION DUE TO GRAVITY )":G=32.2
210 LPRINT"R=53.34 FT-LBF/LBM-DEG R (UNIVERSAL GAS CONSTANT )":                R=53.34
220 LPRINT"C=.54 (DISCHARGE COEFFICIENT; SQUARE EDGED ORIFICE )":C=.54
250 REM ************************************ INITIALIZE VARIABLES
255 LPRINT
256 LPRINT"DEPTH OF SLIP - FT ":INPUT DW:LPRINT DW:PX=(DW/2.3039)+14.7
257 L1=INT(DW/2)
258 L2=L1
259 LPRINT"TOTAL DIFFUSER LENGTH - FT ":INPUT L3:LPRINT L3
260 N3=L3/L1
261 IF N3=INT(N3) GOTO 263
262 N3=INT(N3+1)
263 N2=INT(N3/2)
264 N1=N3-N2
270 LPRINT"FOR THE FIRST DIFFUSER SECTION ENTER THE FOLLOWING:"
271 LPRINT"# OF BUBBLERS = ":N1
272 LPRINT"BUBBLER SPACING = ":L1
273 LPRINT"DIFFUSER DIAMETER (DECIMAL INCHES)":INPUT P1:LPRINT P1
274 LPRINT"ORIFICE DIAMETER (DECIMAL INCHES)":INPUT O1:LPRINT O1
275 LPRINT
280 LPRINT"FOR THE SECOND DIFFUSER SECTION ENTER THE FOLLOWING:"
281 LPRINT"# OF BUBBLERS = ":N2
282 LPRINT"BUBBLER SPACING = ":L2
283 LPRINT"DIFFUSER DIAMETER (DECIMAL INCHES)":INPUT P2:LPRINT P2
284 LPRINT"ORIFICE DIAMETER (DECIMAL INCHES)":INPUT O2:LPRINT O2
285 LPRINT
290 LPRINT"ENTER PARAMETERS AT FIRST BUBBLER AS FOLLOWS:"
291 LPRINT"PRESSURE - PSIG":INPUT PG:LPRINT PG:PA=PG+14.7
292 LPRINT"TEMPERATURE - DEG F":INPUT TG:LPRINT TG:TA=TG+460
293 LPRINT "AIR FLOW - SCFM":INPUT QM:LPRINT QM:QS=QM/60:LPRINT
295 P1=P1/12:A1=(P1*P1*3.14159)/4:O1=O1/12:A2=(O1*O1*3.14159)/4
296 P2=P2/12:A3=(P2*P2*3.14159)/4:O2=O2/12:A4=(O2*O2*3.14159)/4
299 BB=0
300 REM ************************************************************
301 REM ********************************* PROGRAM MAINFRAME ******
302 REM ************************************************************
310 BB=BB+1
311 IF BB>1 GOTO 315
312 LPRINT:LPRINT"DIFFUSER SECTION IS ";P1*12;" INCHES IN DIAM. WITH ";O1*12;" INCH ORIFICES.":LPRINT
315 IF BB>N1 GOTO 350
320 AP=A1:AO=A2:GOTO 400
350 IF BB>N1+1 GOTO 400
352 LPRINT:LPRINT"DIFFUSER SECTION IS ";P2*12;" INCHES IN DIAM. WITH ";O2*12;" INCH ORIFICES.":LPRINT
400 H=(((PA/PX)^((K-1)/K)-1)*(2/(K-1)))^.5
405 IF H>=1 THEN TR=.83333:PR=.52828:GOTO 430
410 TR=(1+((K-1)/2)*(H^2))^-1
420 PR=TR^(K/(K-1))
430 TX=TR*TA
440 SS=(K*G*R*TX)^.5
450 V=H*SS
460 RO=(PA*PR*144)/(R*TX)
470 IF BB>N1 THEN AO=A4 ELSE AO=A2
480 MF=.54*RO*AO*V
```

```
490 QX=(MF^60)/.075:QM=QM-QX
500 IF BB>N1 THEN L=L2 ELSE L=L1
510 GOSUB 1000
520 HL=(L^PL)/100:PG=PG-HL:PA=PA-HL
530 LPRINT:LPRINT
540 IF BB<>1 GOTO 560
550 LPRINT TAB(0)"BUB #";TAB(8)"MACH #";TAB(18)"PRESSURE";TAB(30)"TEMP";TAB(36)"BUBBLER DISCHARGE";TAB(56)"REMAINING CFM"
555 LPRINT
560 LPRINT TAB(1)BB;TAB(6)M;TAB(18)PG+HL;TAB(30)TG;TAB(40)QX;TAB(58)QM
600 IF QM<=0 THEN LPRINT"SYSTEM CAPACITY (CFM) HAS BEEN EXHAUSTED AT THIS BUBBLER.
601 IF QM<=0 THEN LPRINT"TRY A LARGER COMPRESSOR AND RE-RUN PROGRAM.":GOTO 660
610 IF PG<=PX-14.7 THEN LPRINT"SYSTEM PRESSURE EXHAUSTED. MUST BE ABOVE 27 FT (11.7193 PSIG)
611 IF PG<=PX-14.7 THEN LPRINT"TO MAINTAIN DIFFUSER PRESSURE. TRY A LARGER PRESSURE AND RE-RUN PROGRAM.":GOTO 660
620 IFBB<=N1+N2-1 THEN GOTO 300
630 LPRINT:LPRINT"SYSTEM PRESSURE AND CAPACITY REQUIREMENTS HAVE BEEN EXCEEDED.
640 LPRINT:LPRINT"EXCESS PRESSURE IS ";PG;" PSIG"
650 LPRINT"EXCESS CAPACITY IS ";QM;" CFM"
660 END
670 REM ********** PRESS. DROP TABLE MATRIX PENDING
1000 PL=.15:RETURN
```

```
**********************************************************

          L.H.C. BUBBLER SYSTEM STUDY

**********************************************************
          MODEL FOR THE OPTIMIZATION OF BUBBLER
          PARAMETERS ALONG DIFFUSER SECTIONS

THE FOLLOWING LIMITATIONS APPLY :

THE MODEL REPRESENTS A TWO SECTION DIFFUSER
K=1.4 ( POLYTROPIC INDEX OF COMPRESSION )
G=32.2 FT/SEC12 ( ACCELERATION DUE TO GRAVITY )
R=53.34 FT-LBF/LBM-DEG R (UNIVERSAL GAS CONSTANT )
C=.54 (DISCHARGE COEFFICIENT: SQUARE EDGED ORIFICE )

DEPTH OF SLIP - FT
 27
TOTAL DIFFUSER LENGTH - FT
 961
FOR THE FIRST DIFFUSER SECTION ENTER THE FOLLOWING:
# OF BUBBLERS =  37
BUBBLER SPACING =  13
DIFFUSER DIAMETER (DECIMAL INCHES)
 1.5
ORIFICE DIAMETER (DECIMAL INCHES)
 .0625

FOR THE SECOND DIFFUSER SECTION ENTER THE FOLLOWING:
# OF BUBBLERS =  37
BUBBLER SPACING =  13
DIFFUSER DIAMETER (DECIMAL INCHES)
 1
ORIFICE DIAMETER (DECIMAL INCHES)
 .0781

ENTER PARAMETERS AT FIRST BUBBLER AS FOLLOWS:
PRESSURE - PSIG
 12
TEMPERATURE - DEG F
 34
AIR FLOW - SCFM
 68.25


DIFFUSER SECTION IS  1.5  INCHES IN DIAM. WITH  .0625  INCH ORIFICES.


BUB #    MACH #     PRESSURE     TEMP  BUBBLER DISCHARGE   REMAINING CFM
  1     .122978      12           34        .178377           68.0716

  2     .118646      11.9805      34        .172075           67.8996

  3     .114147      11.961       34        .165534           67.734

  4     .109458      11.9415      34        .158718           67.5753

  5     .104559      11.922       34        .151598           67.4237
```

6	.0994195	11.9025	34	.144131	67.2796
7	.0939894	11.883	34	.136244	67.1433
8	.0882291	11.8635	34	.127881	67.0154
9	.0820581	11.844	34	.118924	66.8965
10	.0753798	11.8245	34	.109234	66.7873
11	.0680491	11.805	34	.0986007	66.6887
12	.0598219	11.7855	34	.0866706	66.602
13	.0502538	11.766	34	.0728007	66.5292
14	.0383697	11.7465	34	.0555787	66.4736
15	.0204554	11.727	34	.0296266	66.444

SYSTEM PRESSURE EXHAUSTED. MUST BE ABOVE 27 FT (11.7193 PSIG)
TO MAINTAIN DIFFUSER PRESSURE. TRY A LARGER PRESSURE AND RE-RUN PROGRAM.

****

L.H.C. BUBBLER SYSTEM STUDY

****

MODEL FOR THE OPTIMIZATION OF BUBBLER
PARAMETERS ALONG DIFFUSER SECTIONS

THE FOLLOWING LIMITATIONS APPLY :

THE MODEL REPRESENTS A TWO SECTION DIFFUSER
K=1.4 (POLYTROPIC INDEX OF COMPRESSION)
G=32.2 FT/SEC[2 (ACCELERATION DUE TO GRAVITY)
R=53.34 FT-LBF/LBM-DEG R (UNIVERSAL GAS CONSTANT)
C=.54 (DISCHARGE COEFFICIENT: SQUARE EDGED ORIFICE)

DEPTH OF SLIP - FT
27
TOTAL DIFFUSER LENGTH - FT
961
FOR THE FIRST DIFFUSER SECTION ENTER THE FOLLOWING:
OF BUBBLERS = 37
BUBBLER SPACING = 13
DIFFUSER DIAMETER (DECIMAL INCHES)
1.5
ORIFICE DIAMETER (DECIMAL INCHES)
.0781

FOR THE SECOND DIFFUSER SECTION ENTER THE FOLLOWING:
OF BUBBLERS = 37
BUBBLER SPACING = 13
DIFFUSER DIAMETER (DECIMAL INCHES)
1
ORIFICE DIAMETER (DECIMAL INCHES)
.0938

ENTER PARAMETERS AT FIRST BUBBLER AS FOLLOWS:
PRESSURE - PSIG
17.11
TEMPERATURE - DEG F
34
AIR FLOW - SCFM
68.25

DIFFUSER SECTION IS 1.5 INCHES IN DIAM. WITH .0781 INCH ORIFICES.

BUB #	MACH #	PRESSURE	TEMP	BUBBLER DISCHARGE	REMAINING CFM
1	.521949	17.11	34	1.21212	67.0379
2	.521063	17.0905	34	1.20996	65.8279
3	.520176	17.071	34	1.20779	64.6201
4	.519287	17.0515	34	1.20562	63.4145

6	.517502	17.0125	34	1.20127	61.0098
7	.516607	16.993	34	1.19909	59.8107
8	.51571	16.9735	34	1.1969	58.6138
9	.51481	16.954	34	1.19471	57.4191
10	.513909	16.9345	34	1.19251	56.2266
11	.513007	16.915	34	1.19031	55.0363
12	.512102	16.8955	34	1.18811	53.8482
13	.511194	16.876	34	1.1859	52.6623
14	.510285	16.8565	34	1.18368	51.4786
15	.509374	16.837	34	1.18147	50.2971
16	.508461	16.8175	34	1.17924	49.1179
17	.507546	16.798	34	1.17702	47.9409
18	.506629	16.7785	34	1.17479	46.7661
19	.50571	16.759	34	1.17255	45.5935
20	.504788	16.7395	34	1.17031	44.4232
21	.503865	16.72	34	1.16807	43.2552
22	.502939	16.7005	34	1.16582	42.0893
23	.502012	16.681	34	1.16356	40.9258
24	.501082	16.6615	34	1.16131	39.7645
25	.500149	16.642	34	1.15904	38.6054
26	.499216	16.6225	34	1.15678	37.4487

28	.497341	16.5835	34	1.15223	35.1419
29	.496401	16.564	34	1.14994	33.992
30	.495457	16.5445	34	1.14766	32.8443
31	.494512	16.525	34	1.14536	31.699
32	.493565	16.5055	34	1.14307	30.5559
33	.492616	16.486	34	1.14077	29.4151
34	.491664	16.4665	34	1.13846	28.2767
35	.490709	16.447	34	1.13615	27.1405
36	.489753	16.4275	34	1.13384	26.0067
37	.488794	16.408	34	1.13152	24.8752

DIFFUSER SECTION IS 1 INCHES IN DIAM. WITH .0938 INCH ORIFICES.

38	.487833	16.3885	34	1.62881	23.2463
39	.48687	16.369	34	1.62545	21.6209
40	.485904	16.3495	34	1.62208	19.9988
41	.484936	16.33	34	1.6187	18.3801
42	.483966	16.3105	34	1.61532	16.7648
43	.482993	16.291	34	1.61193	15.1529
44	.482019	16.2715	34	1.60853	13.5443
45	.48104	16.252	34	1.60512	11.9392
46	.48006	16.2325	34	1.6017	10.3375
47	.479078	16.213	34	1.59828	8.73924

49	.477105	16.174	34	1.59142	5.55297
50	.476116	16.1545	34	1.58797	3.965
51	.475123	16.135	34	1.58452	2.38048
52	.474128	16.1155	34	1.58106	.799423
53	.473131	16.096	34	1.57759	-.778166

SYSTEM CAPACITY (CFM) HAS BEEN EXHAUSTED AT THIS BUBBLER.
TRY A LARGER COMPRESSOR AND RE-RUN PROGRAM.

****

L.H.C. BUBBLER SYSTEM STUDY

****

MODEL FOR THE OPTIMIZATION OF BUBBLER
PARAMETERS ALONG DIFFUSER SECTIONS

THE FOLLOWING LIMITATIONS APPLY :

THE MODEL REPRESENTS A TWO SECTION DIFFUSER
K=1.4 (POLYTROPIC INDEX OF COMPRESSION)
G=32.2 FT/SEC2 (ACCELERATION DUE TO GRAVITY)
R=53.34 FT-LBF/LBM-DEG R (UNIVERSAL GAS CONSTANT)
C=.54 (DISCHARGE COEFFICIENT; SQUARE EDGED ORIFICE)

DEPTH OF SLIP - FT
27
TOTAL DIFFUSER LENGTH - FT
961
FOR THE FIRST DIFFUSER SECTION ENTER THE FOLLOWING:
OF BUBBLERS = 37
BUBBLER SPACING = 13
DIFFUSER DIAMETER (DECIMAL INCHES)
1.5
ORIFICE DIAMETER (DECIMAL INCHES)
.0625

FOR THE SECOND DIFFUSER SECTION ENTER THE FOLLOWING:
OF BUBBLERS = 37
BUBBLER SPACING = 13
DIFFUSER DIAMETER (DECIMAL INCHES)
1
ORIFICE DIAMETER (DECIMAL INCHES)
.0781

ENTER PARAMETERS AT FIRST BUBBLER AS FOLLOWS:
PRESSURE - PSIG
17.11
TEMPERATURE - DEG F
34
AIR FLOW - SCFM
68.25

DIFFUSER SECTION IS 1.5 INCHES IN DIAM. WITH .0625 INCH ORIFICES.

BUB #	MACH #	PRESSURE	TEMP	BUBBLER DISCHARGE	REMAINING CFM
1	.521949	17.11	34	.776256	67.4738
2	.521063	17.0905	34	.77487	66.6989
3	.520176	17.071	34	.773484	65.9254
4	.519287	17.0515	34	.772093	65.1533

6	.517502	17.0125	34	.769305	63.6133
7	.516607	16.993	34	.767907	62.8454
8	.51571	16.9735	34	.766505	62.0789
9	.51481	16.954	34	.765101	61.3138
10	.513909	16.9345	34	.763695	60.5501
11	.513007	16.915	34	.762287	59.7878
12	.512102	16.8955	34	.760875	59.0269
13	.511194	16.876	34	.759459	58.2675
14	.510285	16.8565	34	.758042	57.5094
15	.509374	16.837	34	.756622	56.7528
16	.508461	16.8175	34	.755199	55.9976
17	.507546	16.798	34	.753773	55.2438
18	.506629	16.7785	34	.752344	54.4915
19	.50571	16.759	34	.750912	53.7406
20	.504788	16.7395	34	.749478	52.9911
21	.503865	16.72	34	.748041	52.243
22	.502939	16.7005	34	.7466	51.4965
23	.502012	16.681	34	.745157	50.7513
24	.501082	16.6615	34	.743711	50.0076
25	.500149	16.642	34	.742262	49.2653
26	.499216	16.6225	34	.740811	48.5245

28	.497341	16.5835	34	.737897	47.0473
29	.496401	16.564	34	.736435	46.3108
30	.495457	16.5445	34	.734971	45.5759
31	.494512	16.525	34	.733503	44.8424
32	.493565	16.5055	34	.732033	44.1103
33	.492616	16.486	34	.73056	43.3798
34	.491664	16.4665	34	.729083	42.6507
35	.490709	16.447	34	.727603	41.9231
36	.489753	16.4275	34	.726119	41.197
37	.488794	16.408	34	.724633	40.4723

DIFFUSER SECTION IS 1 INCHES IN DIAM. WITH .0781 INCH ORIFICES.

38	.487833	16.3885	34	1.12919	39.3431
39	.48687	16.369	34	1.12686	38.2163
40	.485904	16.3495	34	1.12452	37.0918
41	.484936	16.33	34	1.12218	35.9696
42	.483966	16.3105	34	1.11984	34.8497
43	.482993	16.291	34	1.11748	33.7323
44	.482019	16.2715	34	1.11513	32.6171
45	.48104	16.252	34	1.11277	31.5044
46	.48006	16.2325	34	1.1104	30.394
47	.479078	16.213	34	1.10803	29.2859

49	.477105	16.174	34	1.10327	27.077
50	.476116	16.1545	34	1.10088	25.9761
51	.475123	16.135	34	1.09848	24.8777
52	.474128	16.1155	34	1.09608	23.7816
53	.473131	16.096	34	1.09368	22.6879
54	.47213	16.0765	34	1.09127	21.5966
55	.471128	16.057	34	1.08885	20.5078
56	.470123	16.0375	34	1.08643	19.4213
57	.469115	16.018	34	1.084	18.3373
58	.468104	15.9985	34	1.08157	17.2558
59	.467092	15.979	34	1.07913	16.1766
60	.466075	15.9595	34	1.07669	15.1
61	.465058	15.94	34	1.07424	14.0257
62	.464036	15.9205	34	1.07178	12.9539
63	.463012	15.901	34	1.06932	11.8846
64	.461985	15.8815	34	1.06685	10.8178
65	.460956	15.862	34	1.06438	9.75339
66	.459924	15.8425	34	1.06189	8.6915
67	.458889	15.823	34	1.05941	7.63209
68	.457851	15.8035	34	1.05692	6.57517
69	.45681	15.784	34	1.05442	5.52075

71	.454721	15.745	34	1.0494	3.41943
72	.453672	15.7255	34	1.04689	2.37255
73	.45262	15.706	34	1.04436	1.32818
74	.451565	15.6865	34	1.04183	.286352

SYSTEM PRESSURE AND CAPACITY REQUIREMENTS HAVE BEEN EXCEEDED.

EXCESS PRESSURE IS 15.667 PSIG
EXCESS CAPACITY IS .286352 CFM

```
10 LPRINT"          ##################################################":LPRINT
20 LPRINT"                        BUBBLER SYSTEM STUDY":LPRINT
30 LPRINT"          ##################################################":LPRINT
40 LPRINT"     SIMULATION OF BUBBLER PERFORMANCE"
50 LPRINT:LPRINT:FOR I=1TO1500:NEXT I
60 LPRINT"THE FOLLOWING LIMITATIONS APPLY:":LPRINT
70 LPRINT"G=916 KG/CU M (DENSITY OF ICE)"
80 LPRINT"K=2.18 JOULE-M/SQ M-HR-DEG C (THERMAL CONDUCTIVITY OF ICE)
90 LPRINT"L=334,000 JOULES/KG (LATENT HEAT OF FUSION OF ICE)
100 LPRINT
110 INPUT"ENTER STATION NUMBER";N
120 INPUT"ENTER THE HEAT TRANSFER COEFFICIENT 'H' ";H
130 INPUT"ENTER THE NUMBER OF METERING PERIODS";Z
140 LPRINT
150 C=0
190 DIM TI(15),TA(15),MM(15),MC(15)
210 PRINT"ENTER ALL PERIOD DURATIONS - (DAYS)"
220 FOR I=1TO Z:PRINT"PERIOD #";I,:INPUT TI(I):NEXT I
230 PRINT"ENTER AVERAGE TEMPERATURE FOR EACH PERIOD - (DEG. C)"
240 FOR I=1TO Z:PRINT"PERIOD #";I,:INPUT TA(I):NEXT I
250 PRINT"ENTER ALL ICE THICKNESSES - (MM) - #0 IS CONTROL THICKNESS""
260 FOR I=0TOZ:PRINT"ICE THICKNESS #";I,:INPUT MM(I):NEXT I
300 C=C+1
305 IF C=1 THEN MC(C-1)=MM(C-1)
306 IF C=Z+1 GOTO 1200
310 Q1=H*.35:DT=0-TA(C):Q2=1000*2.18*DT/MC(C-1)
320 L=334000:G=916
330 GC=(Q2-Q1)/(L*G):GC=GC*3600*24*1000
340 GA=(MM(C)-MM(C-1))/TI(C)
350 MC(C)=MC(C-1)+GC
500 IF C=1 THEN GOSUB 900
600 LPRINT C,MC(C),MM(C),100*(MC(C)-MM(C))/MM(C),GC,GA
700 GOTO 300
900 LPRINT:LPRINT"THIS PERFORMANCE TABLE IS AT STATION #";N:LPRINT
1000 LPRINT,"   ICE THICKNESS (MM)",,"ICE DETERIORATION (MM/D)"
1010 LPRINT"PERIOD","CALCULATED","MEASURED","% DIFFERENCE","CALCULATED","MEASURED"
1020 LPRINT"-------------------------------------------------------------------------------"
1030 LPRINT,MM(0),MM(0)
1040 RETURN
1200 LPRINT"END OF PROGRAMME":END
```

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BUBBLER SYSTEM STUDY

****

SIMULATION OF BUBBLER PERFORMANCE

THE FOLLOWING LIMITATIONS APPLY:

G=916 KG/CU M (DENSITY OF ICE)
K=2.18 JOULE-M/SQ M-HR-DEG C (THERMAL CONDUCTIVITY OF ICE)
L=334,000 JOULES/KG (LATENT HEAT OF FUSION OF ICE)

THIS PERFORMANCE TABLE IS AT STATION # 17

	ICE THICKNESS (MM)			ICE DETERIORATION (MM/D)	
PERIOD	CALCULATED	MEASURED	% DIFFERENCE	CALCULATED	MEASURED
	737	737			
1	697.681	711	-1.87329	-39.3191	-26
2	653.802	673	-2.85258	-43.8788	-38
3	607.996	610	-.328529	-45.8061	-63
4	559.694	533	5.00818	-48.3024	-77
5	510.564	432	18.186	-49.13	-101
6	461.913	457	1.07507	-48.6505	25
7	424.856	419	1.3976	-37.0571	-9.5
8	381.258	368	3.60274	-43.5979	-25.5
9	339.279	292	16.1914	-41.9793	-38
10	296.497	216	37.2672	-42.7816	-38
11	263.717	89	196.311	-32.7804	-63.5
12	242.832	178	36.4223	-20.8851	44.5
13	224.999	165	36.363	-17.8328	-6.5

END OF PROGRAMME

****

BUBBLER SYSTEM STUDY

****

SIMULATION OF BUBBLER PERFORMANCE

THE FOLLOWING LIMITATIONS APPLY:

G=916 KG/CU M (DENSITY OF ICE)
K=2.18 JOULE-M/SQ M-HR-DEG C (THERMAL CONDUCTIVITY OF ICE)
L=334,000 JOULES/KG (LATENT HEAT OF FUSION OF ICE)

THIS PERFORMANCE TABLE IS AT STATION # 11

PERIOD	ICE THICKNESS (MM) CALCULATED	MEASURED	% DIFFERENCE	ICE DETERIORATION (MM/D) CALCULATED	MEASURED
	737	737			
1	709.245	699	1.46573	-27.7546	-38
2	676.905	686	-1.32577	-32.3402	-13
3	642.675	673	-4.50593	-34.2301	-13
4	606.09	635	-4.55272	-36.5849	-38
5	568.805	546	4.17675	-37.2852	-89
6	532.045	559	-4.82201	-36.7601	13
7	505.444	521	-2.98584	-26.6012	-9.5
8	473.112	457	3.52568	-32.3314	-32
9	442.02	394	12.1879	-31.092	-31.5
10	410.179	330	24.2967	-31.8413	-32
11	385.447	267	44.3622	-24.7321	-31.5
12	368.363	305	20.7747	-17.084	19
13	352.677	292	20.7799	-15.6856	-6.5

END OF PROGRAMME

****

BUBBLER SYSTEM STUDY

****

SIMULATION OF BUBBLER PERFORMANCE

THE FOLLOWING LIMITATIONS APPLY:

G=916 KG/CU M (DENSITY OF ICE)
K=2.18 JOULE-M/SQ M-HR-DEG C (THERMAL CONDUCTIVITY OF ICE)
L=334,000 JOULES/KG (LATENT HEAT OF FUSION OF ICE)

THIS PERFORMANCE TABLE IS AT STATION # 21

PERIOD	ICE THICKNESS (MM) CALCULATED	MEASURED	% DIFFERENCE	ICE DETERIORATION (MM/D) CALCULATED	MEASURED
	737	737			
1	717.153	686	4.54121	-19.8473	-51
2	692.703	686	.977052	-24.4501	0
3	666.387	673	-.982575	-26.3153	-13
4	637.805	635	.44175	-28.5821	-38
5	608.596	622	-2.15507	-29.2096	-13
6	579.93	610	-4.92958	-28.6659	-12
7	560.633	584	-4.00123	-19.2968	-6.5
8	536.054	559	-4.10483	-24.5788	-12.5
9	512.539	533	-3.83877	-23.5147	-13
10	488.322	508	-3.87367	-24.2176	-12.5
11	470.029	356	32.0307	-18.2923	-76
12	457.826	457	.180795	-12.2032	50.5
13	446.488	381	17.1885	-11.338	-38

END OF PROGRAMME